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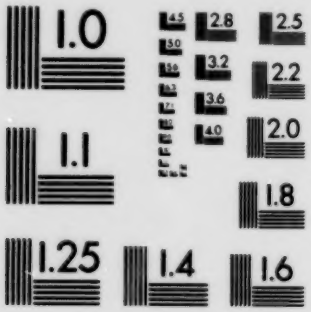

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DIRECT USE OF COAL IN BLAST-FURNACE TECHNOLOGY

W.P. HUTNY AND J.T. PRICE
Combustion and Carbonization Research Laboratory

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DIRECT USE OF COAL IN BLAST-FURNACE TECHNOLOGY

W.P. Hutny* and J.T. Price*

Abstract

This study was undertaken to investigate processes involving coal injection into blast furnaces and to assess the suitability of Canadian coals for this technology. Investigations and operating data from several industrial works are reported.

This paper discusses factors influencing coal injection, particularly coal characteristics, coal combustion, and mechanical systems. Both theoretical and practical aspects have been considered. Criteria for assessing coal based on volatile matter content and ash are discussed and an alternative method is proposed based on a complete characterization of pyrolysis products. The suitability of several Canadian coals for blast-furnace injection has been recognized.

Future research needs are identified.

*Research Scientist, Combustion and Carbonization Research Laboratory, Energy Research Laboratories, CANMET, Energy, Mines and Resources Canada, Ottawa, K1A 0G1.

TECHNIQUES D'INJECTION DIRECTE DU CHARBON DANS LES HAUTS-FOURNEAUX

W.P. Hutny* et J.T. Price*

Résumé

Cette étude a été réalisée dans le but de vérifier les procédés entourant l'injection du charbon dans les hauts-fourneaux. Elle visait également à déterminer dans quelle mesure les charbons canadiens conviennent à cette technique. Le rapport fait état des recherches et données opérationnelles découlant de plusieurs travaux effectués par des entreprises industrielles.

Les éléments qui influent sur l'injection du charbon, en particulier les caractéristiques du charbon, la combustion et les systèmes mécaniques de même que les aspects pratiques et théoriques sont passés en revue. Les auteurs présentent une étude des critères d'évaluation qui reposent sur le contenu en cendre et en matière volatile du charbon et proposent une méthode de rechange basée sur la caractérisation complète des produits résultant de la pyrolyse. L'étude a permis de conclure que les charbons canadiens peuvent être injectés directement dans les hauts-fourneaux.

On recommande de poursuivre les recherches.

*Chercheur scientifique, Laboratoire de recherche sur la combustion et la carbonisation, Laboratoires de recherche sur l'énergie, CANMET, Énergie, Mines et Ressources Canada, Ottawa, K1A 0G1.

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INTRODUCTION

SIGNIFICANCE OF COAL INJECTION

After lengthy development, the blast-furnace operation has changed considerably over recent decades resulting in improved productivity and coke rate. Improvements have become possible by applying new technologies, such as high blast temperature, high top pressure, oxygen enrichment, and improvement in coke quality and in burden preparation. Another factor significantly affecting the blast-furnace process is auxiliary fuel injection through tuyères, which has become an essential part of iron-making technology. The use of tuyères fuel injection reduces coke consumption, minimizes variations in hot metal composition, and provides endothermic reactions to control the energy balance of the combustion zone, which allows the process to run smoothly and efficiently.

The use of an alternative fuel decreases the coke consumption by direct carbon replacement and by allowing higher blast temperatures to be applied. Injection of supplementary fuels into blast furnaces has been practised widely for more than 20 years.

The use of various coke substitutes depends upon:

- economic advantages of each fuel
- technological suitability
- material resources
- capital investment.

Alternative fuel injectants that have been used include natural gas, coke oven gas, tar, oil, and coal. Nearly all these fuels have demonstrated cost advantages over coke but oil has been used most commonly.

In recent years, the cost and availability of various sources of energy have fluctuated and the practice of injecting oil and natural gas has become economically questionable. For example, in Japan in 1981, 32 of 44 operating blast furnaces were converted to all-coke operations. By 1983, nearly all units were converted into oilless technology (1). Similar trends occurred in other countries.

It is worth noting that many blast furnaces worldwide were designed to have tuyère injection. Loss of injectants, by conversion to all-coke operation, has caused many operating problems and has resulted in poorer quality iron, lower production rate, and increased coke rate. Instability in oil prices and dwindling resources (reserves are estimated between 20 and 50 years) (2,3) have forced ironmakers to consider other substitutes for coke. Coal-tar (CTM), coal-oil (COM), and coal-water (CWM) mixtures have been tried with varying degrees of success. Recently, injection of pulverized or granular coal has received the most attention and has been introduced at steel plants in many parts of the world.

Coal injection has specific problems that require sophisticated facilities and, hence, higher capital investment. They include:

- need for handling;
- difficulty of transportation to tuyères to ensure uniform combustion conditions;
- lower combustibility (compared with natural gas and oil);
- presence of mineral matter; and
- unburned residual matter in blast furnace affecting gas flow and bed permeability.

However, in most cases coal is the cheapest, most abundant (reserves are estimated for more than 250 years) (3), and most effective fuel injectant to replace oil. It has a high coke replacement ratio and generally enhances blast-furnace operation.

According to reported data, coal has been injected into 50 blast furnaces in the following countries: 12 in Japan; 7 in the U.K.; 5 each in the USA, West Germany, and China; 4 in France; 3 in the USSR; 2 each in Belgium and Holland; and 1 each in Luxembourg, Poland, Sweden, East Germany, and Australia (charcoal).

Further increases in the use of coal injection are expected. For example, in Japan in 1986, the average rate of injected coal increased 70% from 13.2 kg/t hot metal(HM) in 1985 to 22.4 kg/t (HM) in 1986 (4).

HISTORICAL REVIEW

Coal injection into blast furnaces is not new. First experiments were carried out in France and Belgium in the mid-nineteenth century. At that time, injected coal represented about 10% of the total fuel. The concept of pulverized coal injection (PCI) reappeared in 1948 and 1955 when a few experiments were carried out in the USSR to reduce the coke rate in ferrosilicon production (Dzierzynski Steel Works, USSR) (5). In 1956, pulverized, low-volatile coal was injected into a 330-m^3 ferromanganese blast furnace at Novotula Works in the USSR (6). Using 31% oxygen enrichment, and a coal rate of 189 kg/t of ferromanganese, a coke replacement ratio of 1 was obtained.

Coal was injected into an experimental iron blast furnace of the U.S. Bureau of Mines in 1959 (7). There followed, a year later, a commercial application at the National Steel Hanna Furnace Division (8). Similar trials were carried out at that time on furnaces at La Chasse (9,10) and at Usinor, Louvroil, France, as well as at Stanton and Staveley, England (11,12). In 1962 and 1963, the Weirton Steel Division of National Steel Corporation, USA, introduced PCI to their No. 2 and No. 3 furnaces respectively (13). The next commercial application in the USA occurred in 1964 on a furnace at the Ashland Works of ARMCO (14).

In the 1960's, PCI was also introduced successfully into industrial practice in the People's Republic of China (15). Now, PCI has become a broadly accepted method of improving blast-furnace performance and has attracted the interest of ironmakers throughout the world.

OBJECTIVES

The objectives of this study are fivefold:

- to identify all available information, both theoretical and industrial, on coal injection processes;
- to critique advantages and disadvantages of coal injection technologies;
- to determine and evaluate the criteria used for coal injection;
- to evaluate the suitability of Canadian coals for injection purposes; and
- to develop a strategy for future work needed to assess coal injection technologies within the Canadian context.

OUTLINE OF BLAST-FURNACE PROCESS

MATERIAL BALANCE

The blast furnace is a high-temperature, moving-bed, chemical reactor the function of which is to produce iron of required specifications efficiently. Iron ore, coke, and flux materials are charged at the top of the furnace, air is preheated to between 900° and 1200°C, and auxiliary fuels are blown through tuyères. Carbon monoxide, hydrogen, and nitrogen leaving the combustion zone at very high temperature ascend through the furnace and transfer most of their sensible heat to the descending charge. A representative material balance is shown in Figure 1 (16). Based on an examination of quenched blast furnaces, a typical internal structure of burden materials is shown in Figure 2 (16).

THERMAL CONSIDERATIONS

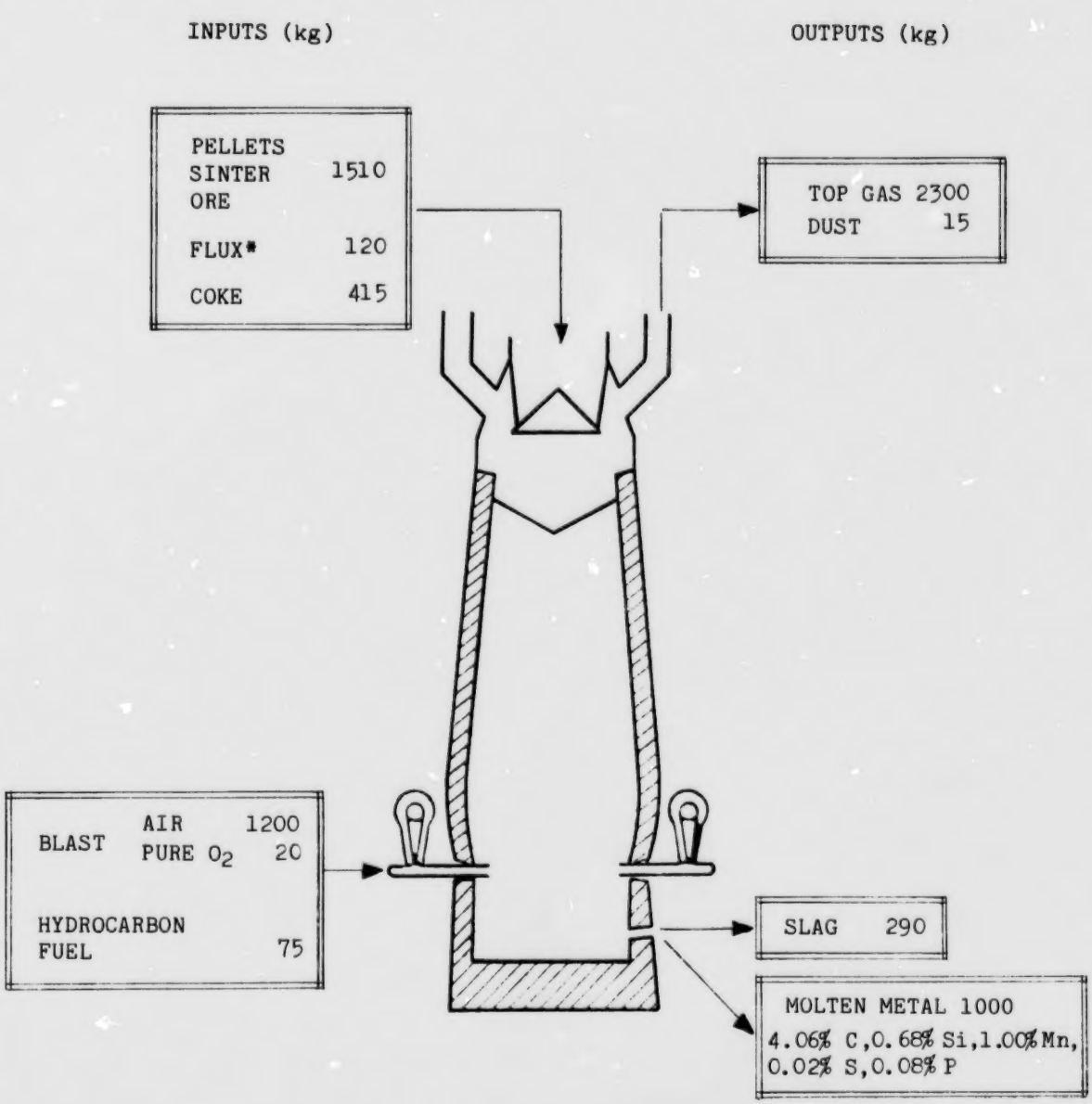
The blast furnace may be considered as counter-current:

- gas/solid heat exchanger from tuyère zone to stockline; and
- oxygen exchanger from fusion to stockline (indirect reduction).

The ascending gas transfers heat to the charge for heating, melting, and endothermic reactions as well as for removing oxygen from iron oxides.

Heat requirements in the blast furnace are met by:

- hot air blown through tuyères; and
- combustion of the coke and fuel injectants.



Slag composition: SiO_2 30-40% MgO 5-15%
Al_2O_3 5-15% S 1-2.5%
CaO 35-45% $NaO+K_2O$ 0-1%

Slag basicity ratio $(CaO+MgO)/(SiO_2+Al_2O_3)$ = 1.1-1.2

Top gas composition: CO - 23%, CO_2 - 22%, H_2 - 3%, H_2O - 3%, N_2 - 49%

Fig. 1 - Material balance for large blast furnace

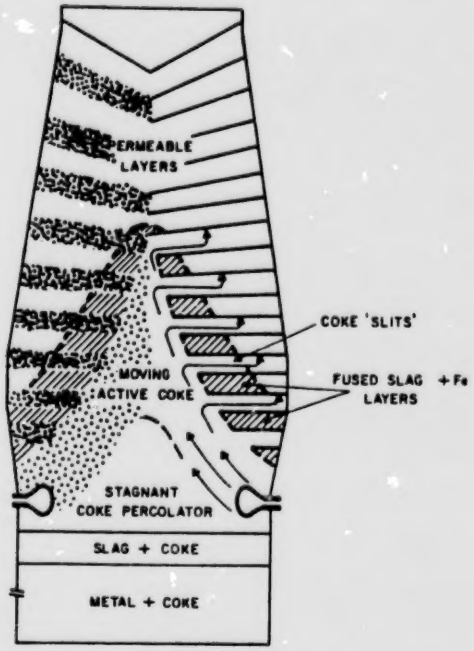


Fig. 2 - Internal structure of large blast furnace

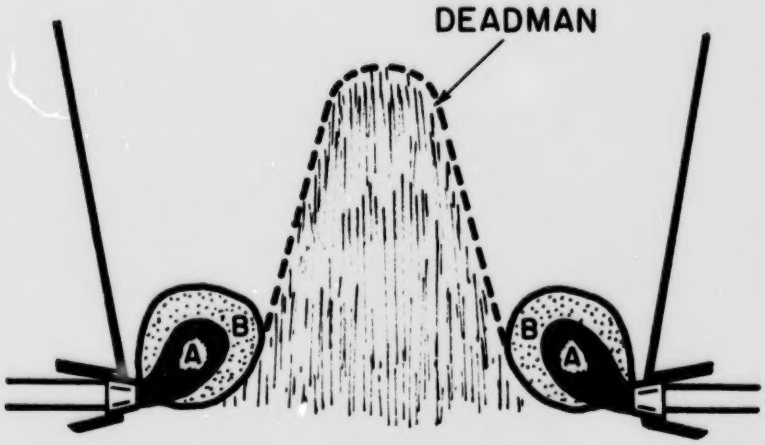


Fig. 3 - Shape of combustion zone

Combustion of fuels takes place in the combustion zone formed by hot air that enters the furnace through tuyères at 150 to 250 m/s velocity and at a pressure of 2 to 4 atm. The high-velocity blast forms a void called a raceway at the outlet of each tuyère, which extends about 1 to 1.5 m into the furnace. Combustion is believed to occur in two zones as shown in Figure 3 (17).

Combustion of carbon in the blast furnace (see Fig. 3) is described by the following reactions:

Zone A:	$C + O_2 = CO_2$	exothermic	$\Delta H^o = -94.05$ kcal
Zone B:	$C + CO_2 = 2CO$	endothermic	$\Delta H^o = +41.21$ kcal
Total:	$C + O_2 = 2CO$	exothermic	$\Delta H^o = -52.84$ kcal

Additional reactions occur if the blast contains moisture or if an injected fuel contains hydrogen:

$H_2 + 1/2\ O_2 = H_2O$	exothermic	$\Delta H^o = -57.8$ kcal
$C + H_2O = CO + H_2$	endothermic	$\Delta H^o = +31.5$ kcal
Total:	exothermic	$\Delta H^o = -25.3$ kcal

Thermal regime in the blast furnace is controlled by temperature in the combustion zone, a convenient measure of which is called the raceway adiabatic flame temperature (RAFT). RAFT is influenced by the blast temperature, auxiliary fuel injection, and other blast parameters such as oxygen and moisture content. RAFT can be calculated from material and heat balances in the combustion zone of the furnace. For every furnace and burden composition, a critical range of operating conditions that must be maintained for satisfactory operation includes:

- maximum limit of RAFT
- minimum limit of RAFT
- minimum quantity of reducing gas.

When maximum RAFT is exceeded, excessively hot tuyère gas causes premature formation of $CaO\text{-}FeO\text{-}SiO_2$ slag in the furnace. Subsequently, FeO is reduced which increases the slag's melting point and causes its solidification. Gas permeability of the burden is reduced resulting in inefficient heat exchange and descent of materials. Another effect of exceeding maximum RAFT is the high vaporization rate of alkalis.

Minimum RAFT is generally recognized as the minimum temperature required to supply the heat needed to maintain a hearth temperature to meet hot metal requirements.

RAFT increases when either blast temperature increases (Fig. 4) (16), or oxygen is added to the blast, or blast humidity decreases. RAFT can be reduced when either blast humidity is increased or auxiliary fuel is injected. Both result in endothermic reactions that cool the furnace. A typical temperature regime within the blast furnace is shown in Figure 5 (16).

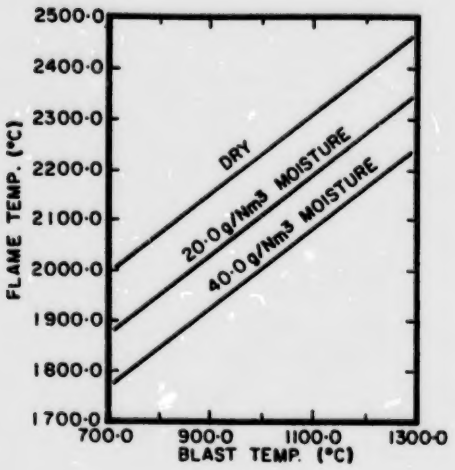


Fig. 4 - Effect of blast temperature and moisture on RAFT

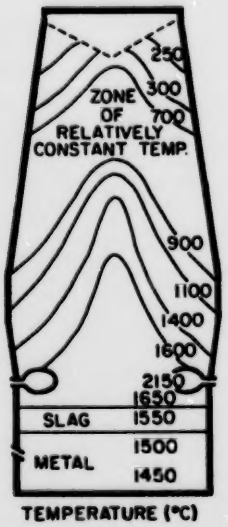


Fig. 5 - Temperature distribution in blast furnace

REDUCTION REACTIONS

Considering the blast furnace as a chemical reactor, the importance of some reactions should be emphasized (17).

Indirect Reduction

In the stack of the blast furnace, iron oxide material is reduced by CO to form CO_2 according to the following equation:

$$FeO + CO = Fe + CO_2 \text{ exothermic}$$

By definition, indirect reduction occurs when CO_2, the product of this reaction, leaves the furnace without further reaction with carbon, which normally occurs at temperatures below 850° to 900°C.

Solution Loss Reaction

The solution loss reaction produces carbon monoxide from carbon dioxide reacting with carbon (coke) above 850° to 900°C; it is very endothermic:

$$C + CO_2 = CO \text{ endothermic}$$

Direct Reduction

In the lower part of the furnace at very high temperature, iron and carbon monoxide are produced by carbon reacting directly with iron oxides. For example:

$$FeO + C = Fe + CO \text{ endothermic}$$

Analysis of the equations for indirect reduction, solution loss reaction, and direct reduction shows that indirect reduction followed by solution loss reaction is chemically and thermodynamically the same as for direct reduction by carbon.

It is advantageous from the thermal point of view that indirect reduction should occur rather than direct reduction because the former is exothermic and lowers the overall heat requirements for the blast furnace. Indirect reduction can be increased by having a well-sized and well-distributed burden to improve gas flow and temperature distribution in the furnace. However, equilibrium conditions for a given temperature limit the amount of indirect reduction that can be achieved. Introduction of hydrogen into the furnace shifts the equilibrium in favour of reactions involving indirect reduction.

ALL-COKE OPERATION

It is commonly accepted in industrial practice (18-20) that all-coke operation is less stable than operation with auxiliary fuel injection. Difficulties can occur in all-coke operations with flame temperature, control of silicon content in the metal, temperature distributions, and slippage of the burden, which results in reduced production of hot metal and increased fuel rates.

PRINCIPLES OF COAL INJECTION

MECHANICAL SYSTEMS

In applying coal injection techniques to commercial blast furnaces, the following processes are essential:

- storage and discharge of raw coal;
- pulverization and drying of the coal;
- transportation, storage, and supply of PC to the injection system;
- safety and protection from explosions;
- uniform distribution or control of PC to each tuyère; and
- combustion of PC.

Several mechanical systems of coal pulverization and distribution have been developed and can be divided into two types: pressurized type and mechanical feeders.

The Petrocarb, Babcock & Wilcox, Chinese, and Soviet systems are pressurized types and depend on pneumatic conveyance of the coal. Koppers have developed a mechanical feeder system in which the principal component is a coal pump. In this system, the injection rate is controlled by varying the speed of the pump. Details of injection systems and their application are described in detail under "Mechanical Systems."

COMBUSTION

Uniform distribution of coal to each tuyère for combustion is particularly important for effective operation of the furnace. Coal is injected through tuyères directly into the raceway (Fig. 6) (21). A coal particle leaving the injection lance enters the blowpipe where it absorbs heat and begins to devolatilize and burn. This process, initiated in the blowpipe, is completed in the raceway.

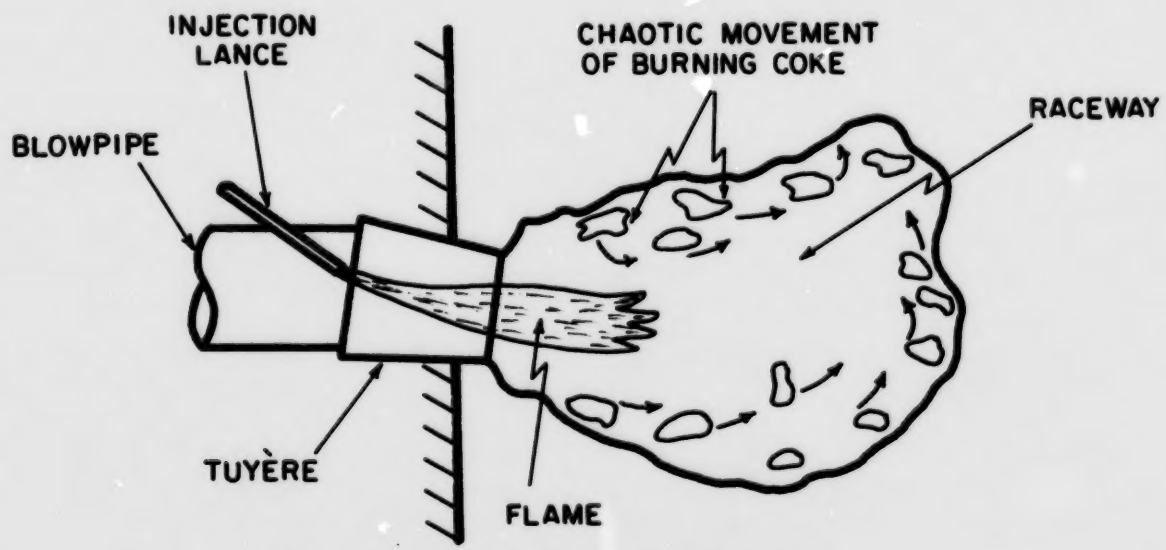


Fig. 6 - Blast-furnace combustion zone

For injected coal to burn effectively in a blast furnace, it is necessary to apply an extremely efficient combustion technology because the time for combustion is limited to milliseconds and the space available is restricted. The efficiency of coal combustion depends on three factors as detailed in Figure 7:

- coal properties
- combustion conditions
- design of combustion devices.

Lifetime of blowpipes, injection lances, and tuyères, and the deposition of ash in these units must be considered during process design as well as factors that optimize combustion efficiency.

Complete combustion is as important for effective gas flow and temperature distribution within the furnace as for satisfying heat requirements of the process. Incomplete combustion may produce soot which blocks raceways and decreases burden permeability. The effect of PCI on the gas composition profile of the tuyère zone of an operating blast furnace is shown in Figure 8 (18). The focal point of combustion, defined as the point at which the concentration of carbon dioxide is at maximum, moves closer to the tuyère tip as the amount of injected coal is increased.

CHEMICAL MODIFICATION OF THE BLAST-FURNACE PROCESS

Partial replacement of coke by injected coal brings about considerable changes in physical and chemical conditions within the blast furnace. Coal, as a hydrogen-bearing fuel, changes the composition and properties of the tuyère gas. Thermochemical data indicate that hydrogen is a more effective reducing agent than is carbon monoxide. The reaction of hydrogen regeneration from water and carbon:

$$H_2O + C = CO + H_2$$

is less endothermic and proceeds faster than the carbon monoxide regeneration (solution loss) reaction:

$$CO_2 + C = 2CO$$

When the auxiliary fuel injection rate increases, the amount of oxygen removed with water as a final product increases at the expense of direct reduction by carbon or via reduction associated with the solution loss reaction (Fig. 9) (22). Thus, the hydrogen regeneration reaction displaces the carbon dioxide solution loss reaction, which decreases the thermal requirements of the process. This feature of fuel injection is perhaps even more attractive than replacing coke carbon units by coal carbon units. Both C-O and C-O-H systems are considered earlier.

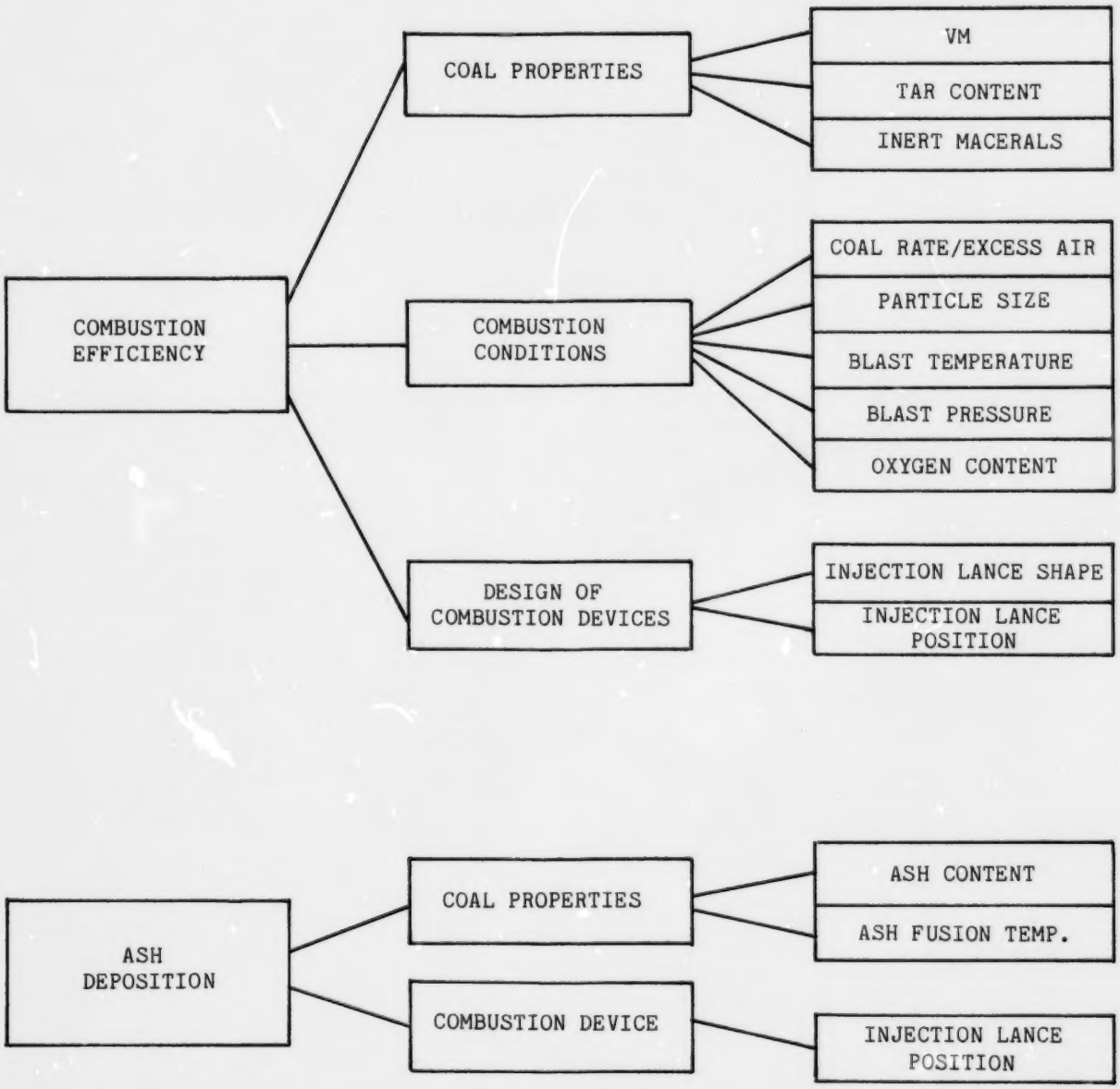
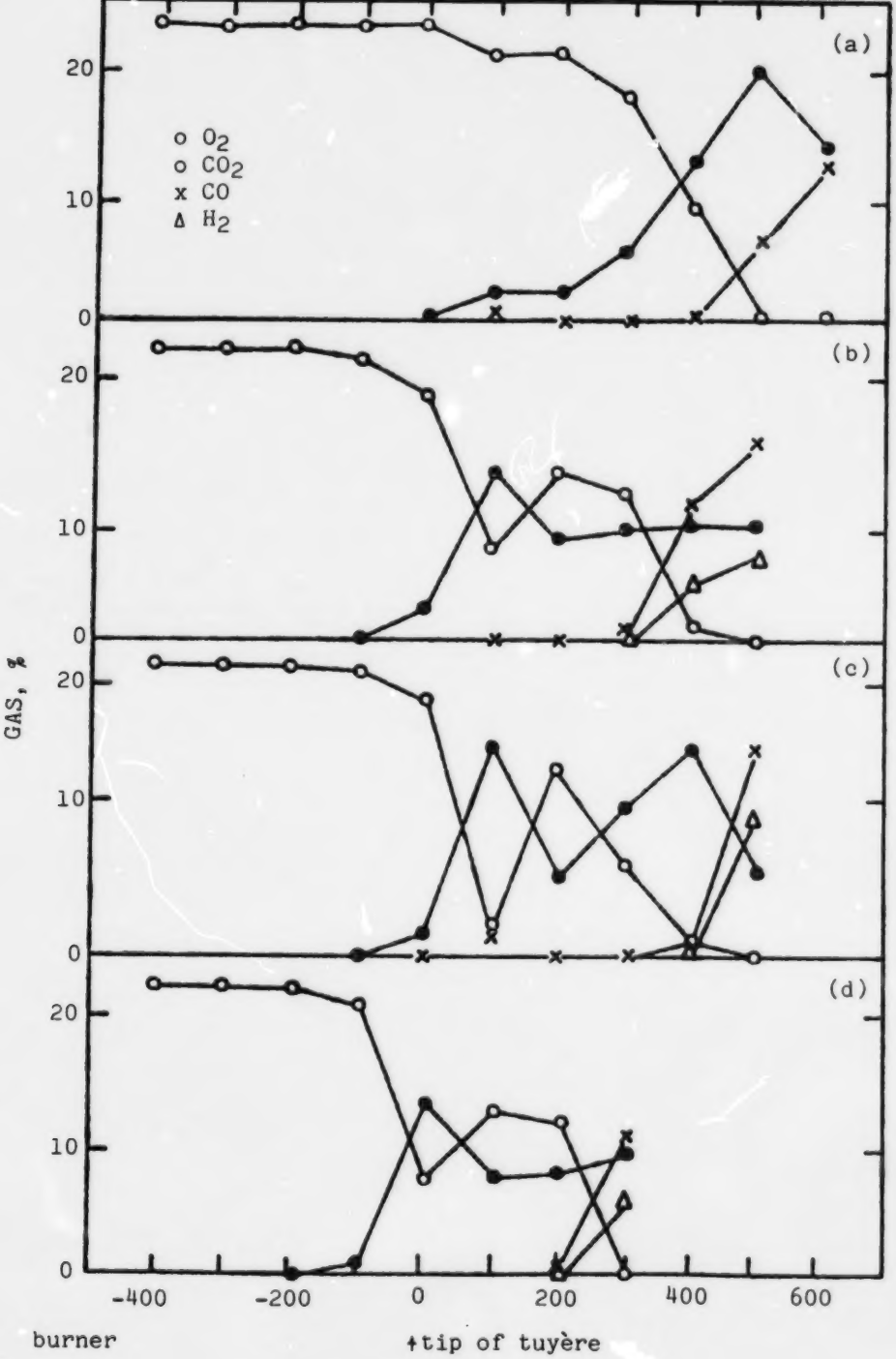


Fig. 7 - Factors affecting coal combustion in blast furnace



no Injection; b 200 kg/h^{-1}; c 300 kg/h^{-1}; d 400 kg/h^{-1}

Fig. 8 - Changes in gas composition in front of tuyère for Chiba (Japan) No. 2 blast furnace

Increased amounts of hydrogen in the furnace imply changes in the reduction process. Blast-furnace conditions including type of reduction, amount of solution loss, flame temperatures, and gas utilization efficiencies are compared in Figures 10 and 11 (23) for all-coke operation, oil injection, and PCI, which comparison shows that:

- highest indirect reduction (59%) and lowest direct reduction (34%) rates occur for PCI;
- indirect and hydrogen reduction increases but direct reduction decreases as hydrogen input increases; and
- rate of solution loss reaction is accordingly lowest for coal injection.

THERMAL MODIFICATION OF THE BLAST-FURNACE PROCESS

The blast-furnace production rate is directly related to the rate of heat input. The most efficient furnace operation is performed at maximum RAFT limit for the particular burden conditions (Fig. 12) (24). The most efficient method to increase RAFT is to raise the blast temperature.

Unfortunately, RAFT can not be endlessly raised above its practical maximum without operating consequences such as hanging, slipping, and ultimate loss in production. To maintain a high blast temperature without exceeding maximum RAFT, endothermic reactions must take place in the combustion zone. Historically, steam, the first coolant introduced through tuyères, was replaced by more efficient auxiliary fuel injection. Endothermic reaction between water and carbon cools the raceway and lowers the temperature of gases leaving the combustion zone. Blast temperature can be increased and blast moisture decreased without causing operational difficulties.

Among combustible injectants, natural gas has the greatest cooling effect on the raceway, followed by oil and coal as shown in Figure 13 (25). The effect of coal, oil, and coal-oil mixtures on flame temperature as derived from theoretical models is shown in Figure 14 (26). In general, fuels having a high C:H ratio have a low cooling effect on the raceway.

COAL INJECTION RATE

Coal has a higher C:H ratio and a smaller cooling effect on flame temperature than other fuels and, consequently, can be injected in larger quantities as results from computer models show (Fig. 15) (27).

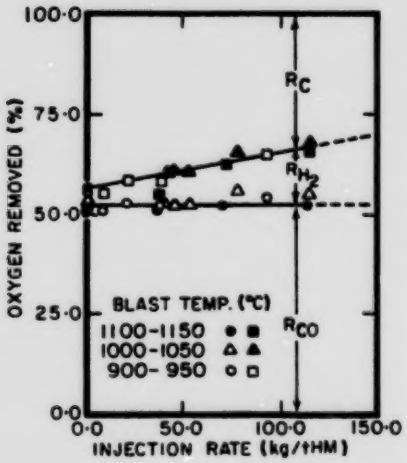


Fig. 9 - Relationship between the mode of oxygen removal and injection rate

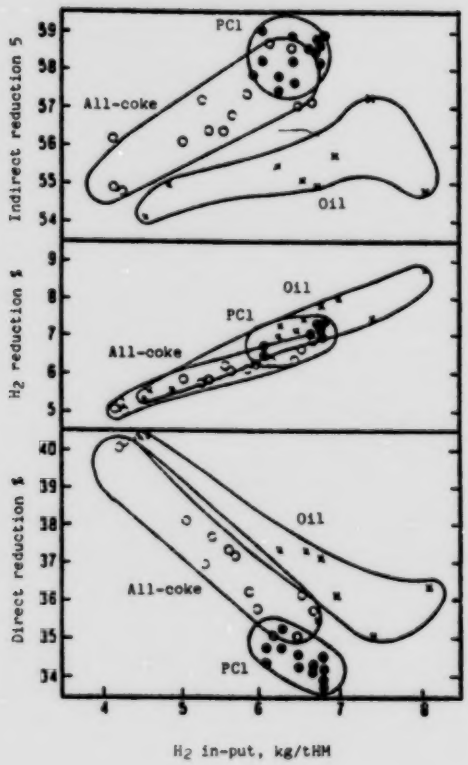


Fig. 10 - Effect of hydrogen input on the reduction process at Oita (Japan) No. 1 blast furnace

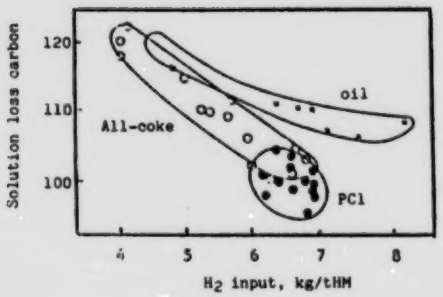


Fig. 11 - Relationship between hydrogen input and solution loss reaction

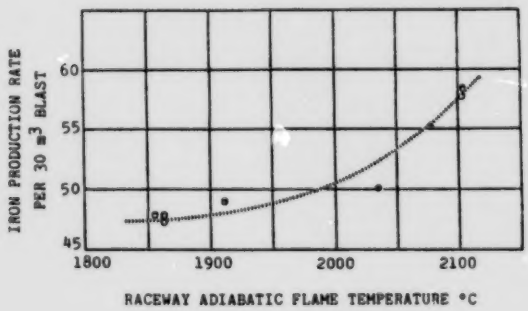


Fig. 12 - Relation of iron production to RAFT

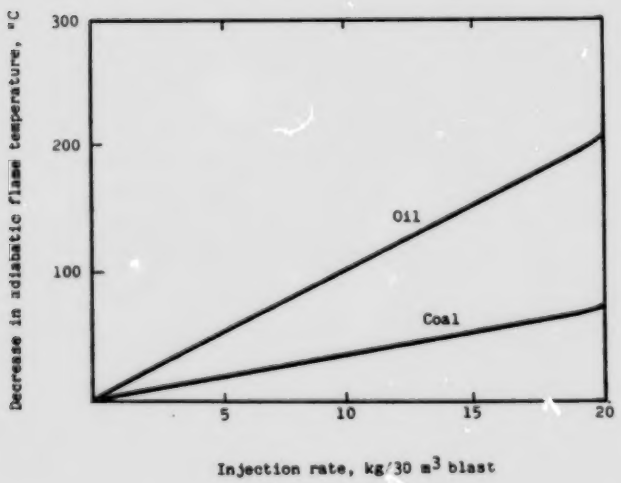


Fig. 13 - Effect of injected fuels on blast-furnace RAFT

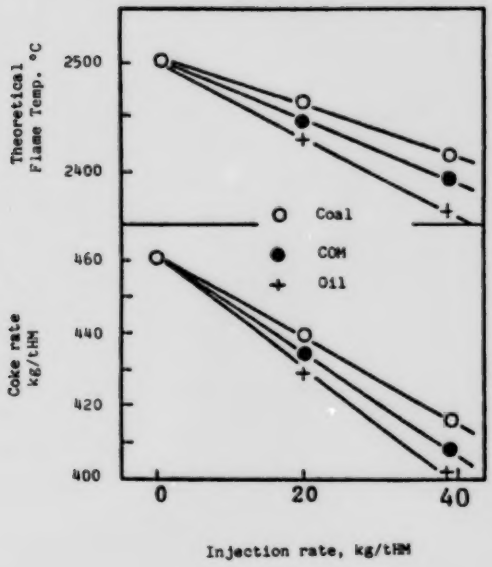


Fig. 14 - Change of RAFT with injection rate

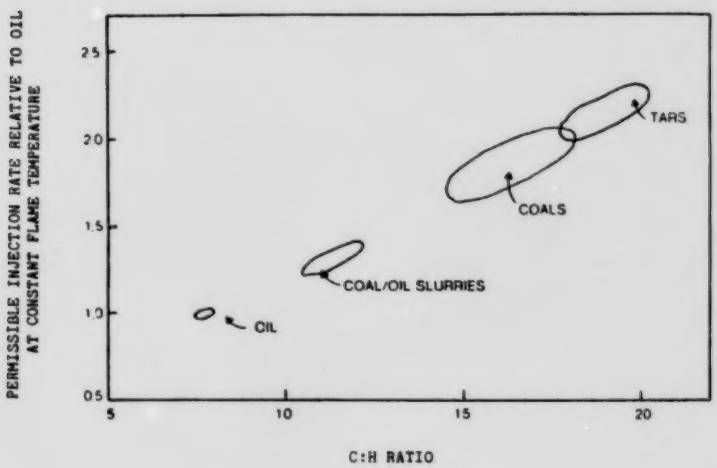


Fig. 15 - Fuel injection rates relative to oil at constant RAFT

Anthracites have the least cooling effect among coals (the highest C:H ratio) and can be injected in large quantities to maintain the optimum RAFT, provided that either increased blast temperature or decreased moisture in the blast is used. Generally, injected coal rates range between 24 and 182 kg/tHM (see Appendix A, Table A-7), but up to 279 kg/tHM of anthracite (45.2% of the total fuel rate) has been used in China (28). When injection rate exceeded 45% of the total fuel rate, coke rate increased, replacement ratio decreased, and smooth operation could not be maintained (28).

The relationship between the PCI rate and some operating factors determined for Oita No. 1 blast furnace is shown in Figure 16 (23). RAFT dropped when PCI rate exceeded 30 kg/tHM, the point at which the blast temperature reached its upper limit. A further drop occurred at PCI rate of 60 kg/tHM when the dehumidifying equipment reached the limit of its capacity.

To determine the optimum rate of coal injection, coal combustibility and stoichiometric ratio must also be considered as well as flame temperature requirements. An increase in the coal rate above the optimum determined for particular operating factors may lead to incomplete combustion causing poor burden permeability and improper gas flow and temperature distribution within the furnace.

The importance of the proper coal rate for the process is illustrated in Figure 17 (20). It shows that a major improvement in blast-furnace performance occurred when PCI was increased from 50 to 70 kg/tHM. The higher rate lowered the cohesive zone and contributed to the expansion of the lumpy zone and, consequently, to the improved use of carbon monoxide in the furnace. Such a low profile of the cohesive zone is essential to achieve a low fuel rate.

REPLACEMENT RATIO

Coke serves several purposes in a blast furnace and, with current technology, only a portion of its total amount (30-40%) can be replaced by coal.

The replacement ratio is defined as the ratio of the mass of coke saved to the mass of an injectant needed to replace it. It depends on a complex interplay of chemical and physical processes and is influenced by:

- coal quality (ash content, C:H ratio)
- combustion conditions and coal burnout
- burden quality and gas flow distribution
- RAFT.

The influence of coal ash content on the replacement ratio has been proven theoretically and experimentally and is discussed in detail later. Fletcher and Garbee have related the replacement ratio to the ash content of coal and coke according to the formula (29):

$$\text{coke/coal replacement} = 1.48 - 0.666\ (\%\ \text{coal ash}/\%\ \text{coke ash}).$$

This relationship was derived from data obtained in full-scale investigations using high-volatile coals (34.7-38.3%) containing 4.6 to 9.8% ash.

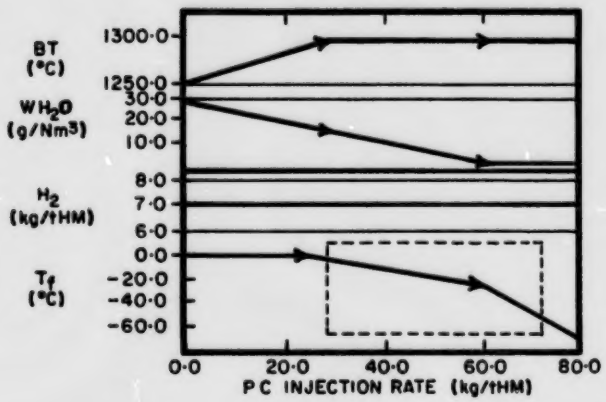


Fig. 16 - Relationship between PCI rate and RAFT for Oita No. 1 blast furnace

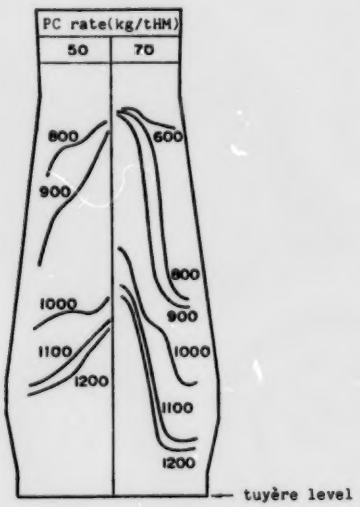


Fig. 17 - Influence of coal injection rate on temperature distribution at Kobe No. 3 blast furnace

Another empirical formula relates coke replacement ratio to coal ash content (30):

coke/coal replacement = 1.037 - 0.01576 x coal ash.

It is based on the following average operating data: coal carbon 84.90%, coal ash 12.63%, coal sulphur 0.65%, blast temperature 1045°C, oxygen enrichment 0.69%, slag basicity 1.0, CO/CO_2 of 1.47.

Figure 18 (31) relates the C:H ratio of coal to the replacement ratio based on theoretical calculation showing that anthracite can displace more coke than coals with higher contents of volatile matter (VM). Figure 19 (27) is a schematic diagram from a computer model showing the predicted coke replacement rates for low- and high-ash coals and other fuels as a function of their carbon and hydrogen contents.

However, the total possible coke replacement per tonne of hot metal is related to the total fuel rate as well as to the coke replacement ratio per unit mass of fuel injected. Figure 20 (27) shows the total coke replacement relative to oil (predicted by computer model) as a function of the carbon and hydrogen contents of the injected fuel. Evidently, coals and tar offer the highest total coke replacement at constant RAFT.

Figures 19 and 20 show that although coal replaces less coke per unit mass of injectant than does oil, it can be injected in larger amounts which leads to a higher total coke replacement.

Results from full-scale experiments (Fig. 21) (15) indicate that the coke replacement ratio is directly proportional to RAFT. Supporting evidence comes from other workers who showed that the replacement ratio decreased if the thermal state of the furnace hearth was inadequate (32).

INFLUENCE OF COAL INJECTION ON COKE QUALITY REQUIREMENTS

Coke fulfils a number of requirements in the blast furnace including:

- major fuel supply providing heat and energy for the process;
- reductant and source of reducing gas; and
- support and permeable component of blast-furnace burden.

Coke is the only material that descends to the lower part of the furnace in its original solid form and becomes the most permeable material of all burden components. For this reason, the quality of coke (its ability to resist disintegration in the blast furnace) is regarded as a critical factor for the operation. In the blast furnace, degradation of coke reduces its permeability which changes not only the distribution of ascending gas, but also the heat transfer, the temperature distribution, and the profile of the softening-melting zone. The solution loss reaction is estimated to remove about 20 to 30% of coke carbon which should decrease coke size by only 3% (33). Coke size typically changes 20% as a result of degradation or weakening, which indicates that solution loss reaction also indirectly influences weakening of coke.

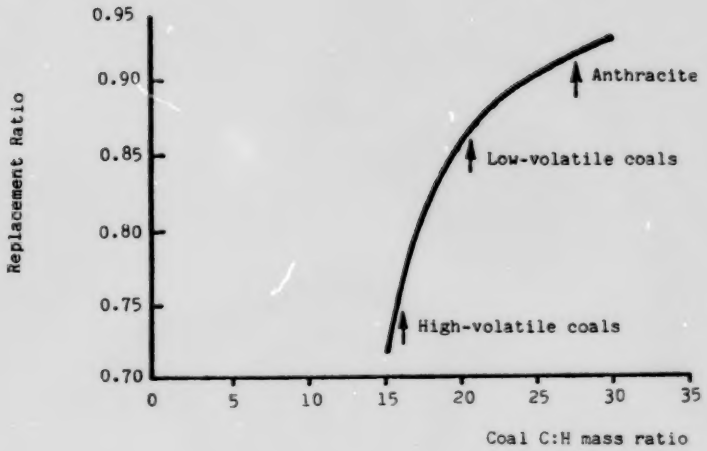


Fig. 18 - Coke replacement ratio as a function of coal's C:H ratio

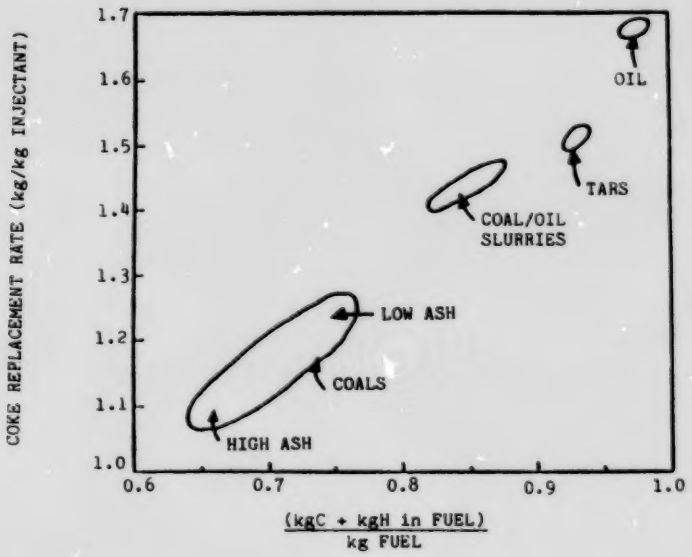


Fig. 19 - Coke replacement rates per unit mass of fuel injected

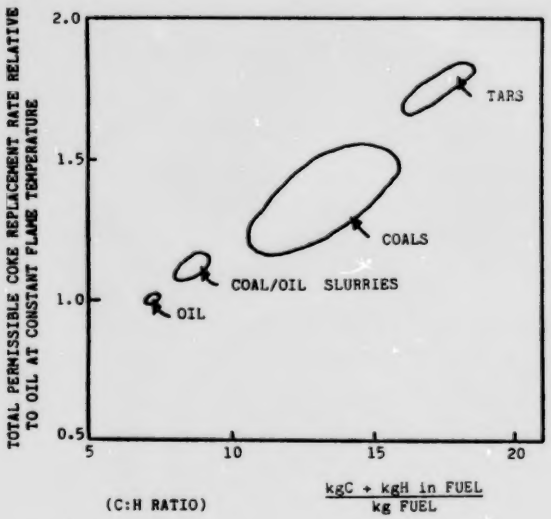


Fig. 20 - Total possible coke replacement ratio relative to oil at constant RAFT

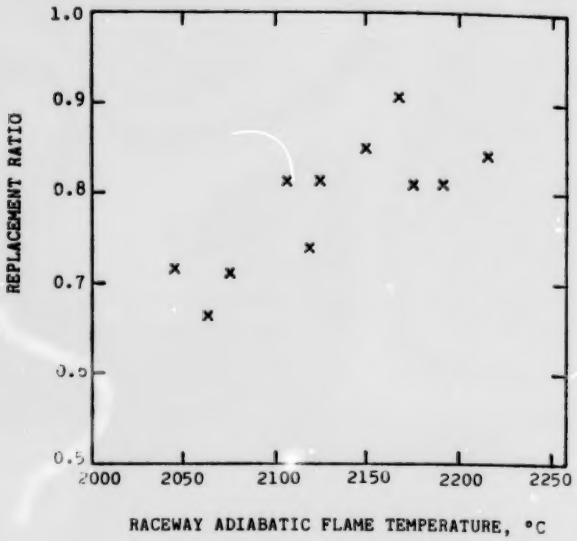


Fig. 21 - Variation of replacement ratio with RAFT

When coal is injected into the blast furnace (see Figs. 10 and 11), the rate of the solution loss reaction is reduced in favour of indirect reduction. Thus, burden permeability would be improved (or coke strength would not need to be as strong) with coal injection because coke would not be weakened so much by solution loss. However, this theory has not been verified by any experimental evidence and further investigations are required.

MECHANICAL SYSTEMS

GENERAL CONSIDERATIONS

Coal injection is more complicated and requires more stringent control than does either oil or natural gas to secure efficient and stable operation of the blast furnace (1). In using PCI, the following concerns must be addressed:

- appropriate particle size distribution;
- prevention of coal explosion;
- continuous operation at pressure encountered in blast furnaces;
- injection of equal quantities of coal into each tuyère irrespective of normal fluctuations in blast pressure;
- ease of setting a desired rate of injection;
- automatic control of the rate of injection during abnormal furnace conditions;
- accurate indication and recording of the weight of injected coal;
- ability to handle all ranks of coal;
- automatic operation; and
- compactness of the whole installation.

The most important aspect of PCI is the prevention of disasters to people and equipment caused by explosion or fire. Risk of explosion or fire is affected by coal size, moisture content, type of coal, and ignition source. Consequently, the following precautions for the prevention of explosion have been established:

- use of air-proof vessels operating under vacuum conditions;
- control of the oxygen concentration in each process unit; and
- removal of all ignition sources, such as metal chips and static electricity.

A common operating problem encountered in industrial operations is line plugging, which may be caused not only by oversized material but also by an increased moisture content. In practice, moisture content above 3% causes the formation of small coal balls that restrict the flow of coal at the injection tank's outlet (8). The best way to avoid a plugging problem is to maintain moisture at about 1%.

Both mechanical (Koppers) and pneumatic feeders (Babcock & Wilcox, Petrocarb, Chinese, and others) have been applied in industrial systems.

PETROCARB SYSTEM

The Petrocarb system (8,11,12,20,24,34,35,36-39) (Fig. 22) (34) consists of two subsystems: a preparation plant and a distribution and injection subsystem (Fig.23) (8,38).

Raw coal is supplied to a preparation plant where it is crushed to a desired size and dried. Both impact-type crushers (8,36,38) and roller mills (1,20,34) have been used, and the latter have been found to be advantageous over other types. These mills have built-in classifiers to control particle size. Coal can be simultaneously pulverized and dried by low-temperature gas. Exhaust gas (about 130°C) from Cowper stove is usually used as a source of heat but other auxiliary gases can be used (1,20). For safety, temperature at both inlet and outlet of the roller mill is controlled.

The storage and primary injectors are the heart of the distribution and injection subsystem (see Figs. 22 and 23). When the amount of coal within the primary injector falls to a predetermined quantity, indicated by load cells, the storage injector automatically discharges coal into the primary injector. Then, the storage injector is automatically refilled. The storage injector is alternately under vacuum or pressure. When coal is being delivered to the storage injector, it is under vacuum pressure; when coal is transferred to the injection tank, the storage injector is pressurized. The primary injector is always under pressure. Coal is continuously carried by air to the furnace from the primary injector through individual pipes to each tuyère. At first, two storage and primary injectors were used (see Fig. 23). One line supplied odd-numbered and the other even-numbered tuyères. Now, the system has been simplified by having only one line (see Fig. 22).

The rate of coal injection measured by load cells is controlled by the differential pressure between the hot blast and the injector. If the rate of injection deviates from controlled levels, the pressure in the primary injector is changed to correct the feed rate. When the pressure in a hot blast increases, the pressure in the primary injector is automatically increased in the same proportion. The reverse compensation takes place when the pressure in the hot blast decreases. Kobe Steel Corporation modified the differential-pressure control of the Petrocarb system by developing a weight injection control (Fig. 24) (1).

The primary injector is continuously flushed with inert gas (nitrogen). The gas not only pressurizes the vessel but also partly fluidizes coal and reduces oxygen concentration below the explosion limit. In the Petrocarb installation, a safety system (8,36) closes valves at the bottom of the primary injector whenever any of the following conditions occur:

- failure of plant air;
- failure of instrumentation of air supply; or
- excessive or low pressure in the hot blast main.

MODIFICATIONS OF PETROCARB SYSTEM

Some modifications of the Petrocarb system have been made at Stanton, U.K., where a combined crusher and dryer has been used (36).

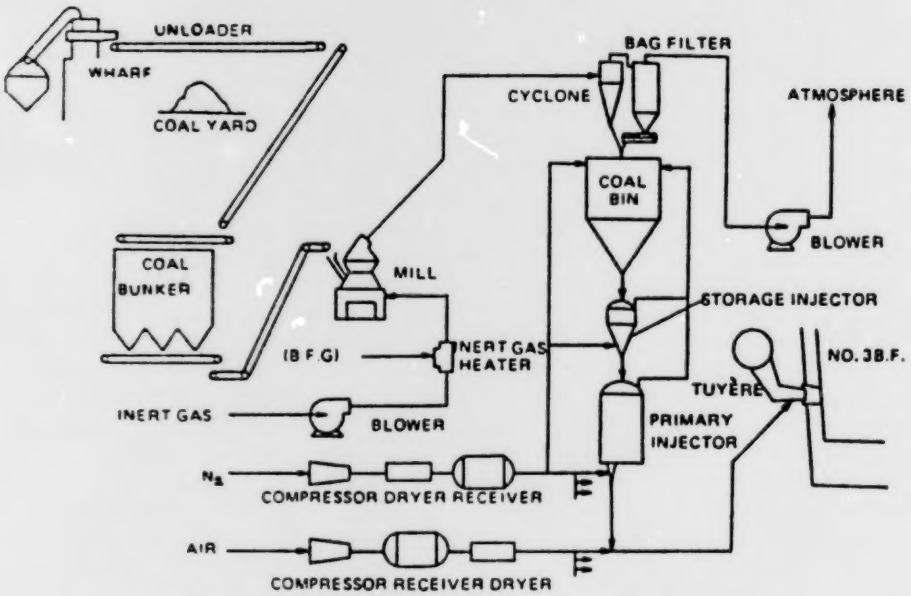


Fig. 22 - Flow diagram of PCI system at Kobe No. 3 blast furnace

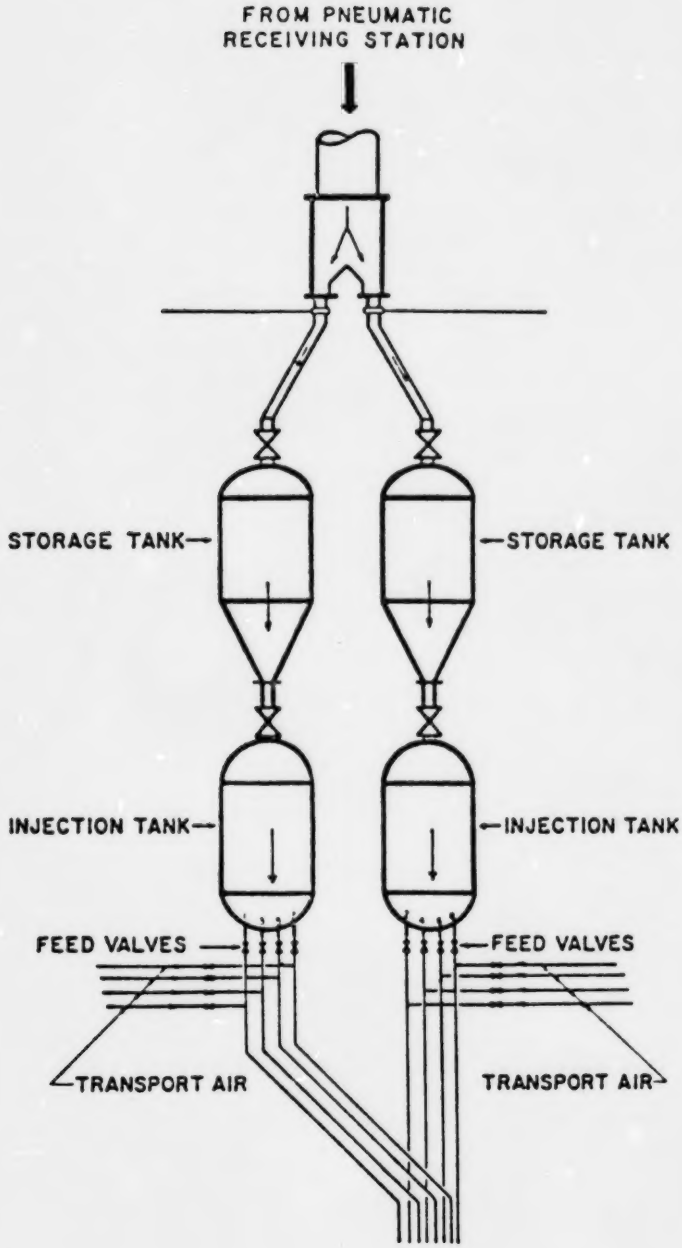


Fig. 23 - Petrocarb coal distribution and injection subsystem

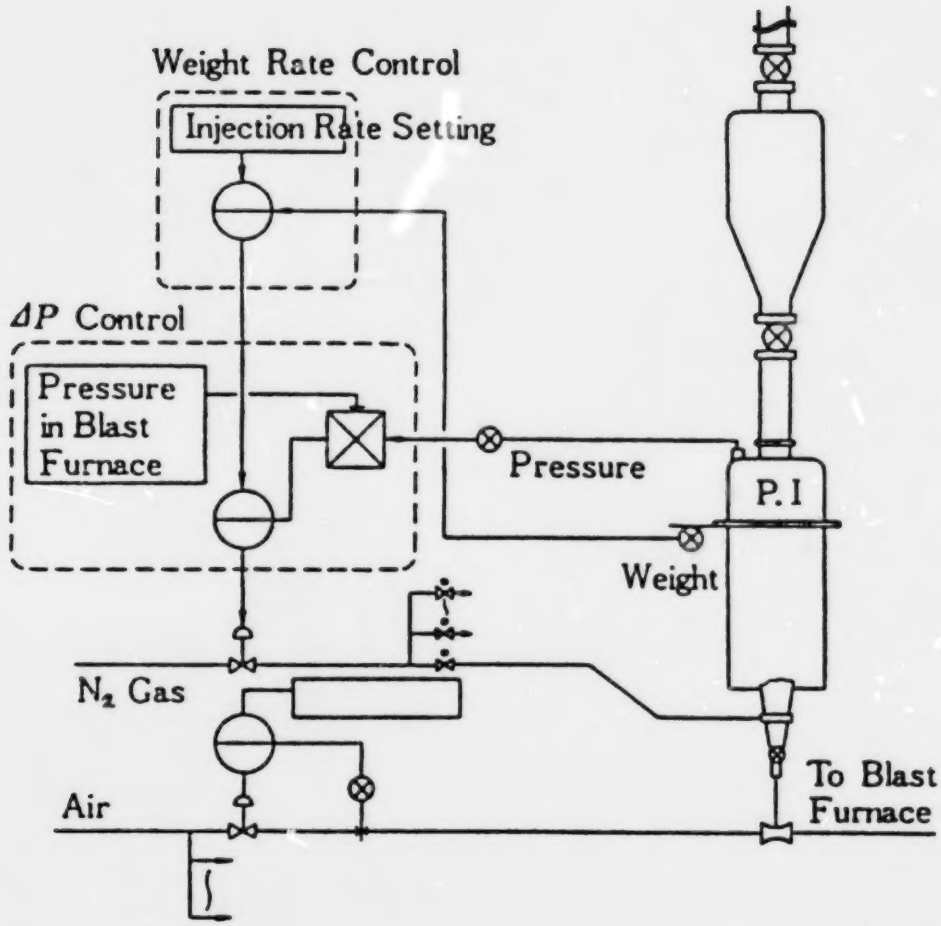


Fig. 24 - Modified Kobe-Petrocarb control system of injection rate

KAWASAKI SYSTEM

The multi-purpose-injection (MPI) system developed by Kawasaki Steel Corporation and Denka Engineering (40,41) allows various kinds of powder (coal, iron ore fines, and calcium carbonate) to be injected through tuyères. The purpose of injecting those materials is to control the content of silicon and sulphur in hot metal. The distribution and injection system is shown in Figure 25 (40) along with the flow diagram of the entire MPI system (Fig. 26) (40). The injection rate is controlled pneumatically by adjusting the rate of transporting gas, which eliminates mechanical devices. Figure 27 (40) is a flow diagram of powder injection control. Total injection rate is controlled to ±1% of the maximum rate.

ARMCO-BABCOCK & WILCOX SYSTEM

In the early 1960's, ARMCO and Babcock & Wilcox developed and applied industrially the coal injection system described by Bell et al. (14). It consisted of two parallel systems, each operated independently of the other and supplying 8 of 16 tuyères of the Bellefonte furnace. All components except the raw coal bins and the wet scrubber operated under elevated pressure (about 1 atm above the bustle pipe pressure). Experience with the first version of the coal injection system led to a drastic change in the concept. The modified coal injection system (42-46) depends entirely on pneumatic transport with high- and low-pressure subsystems. The low-pressure subsystem (Fig. 28) (45) encompasses heating, drying, and pulverizing of coal as well as storage in a purged, pulverized coal reservoir (45). Two coal-pulverizing lines are applied to avoid shut down of the system during inspection or maintenance.

The high-pressure subsystem, outlined in Figure 29 (45), has three feed tanks that are filled with dry, pulverized coal from the reservoir. The feed tanks operate in sequence. Thus, when one tank injects coal to the furnace, another tank is filled with coal and pressurized, ready to inject. At this time, the third tank is in the process of filling with pulverized coal. Compressed air is used to transport coal to blowpipes of the furnace. The rate of injection is controlled by varying pressure in the feed tanks. Inert gas is used for pressurizing both feed tanks and storage reservoir. Major differences between the injection system applied at the Bellefonte furnace and the modified version (Amanda furnace) are listed in Appendix Table A-1 (44).

Figures 30 and 31 (43) show the ARMCO - Babcock & Wilcox system that is installed at Hoogovens Steel Works, Holland. An essential element of this system is the distributor, which ensures uniform injection of coal through all tuyères around the furnace. As reported (43,46), the ARMCO - Babcock & Wilcox system ensures acceptable accuracy of coal distribution (Fig. 32) (43).

KOPPERS SYSTEM

The Koppers system (13,24,35,39) applied initially at Weirton Steel Division, USA (39), uses the coal feeder developed by the Locomotive Development Committee of Bituminous Coal Research Inc. The principal components of the system are shown in Figure 33 (39).

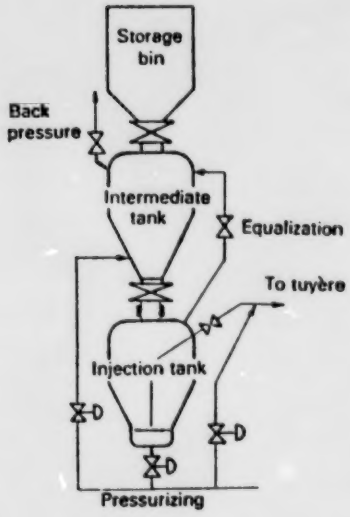


Fig. 25 - Distribution and injection subsystem of MPI system

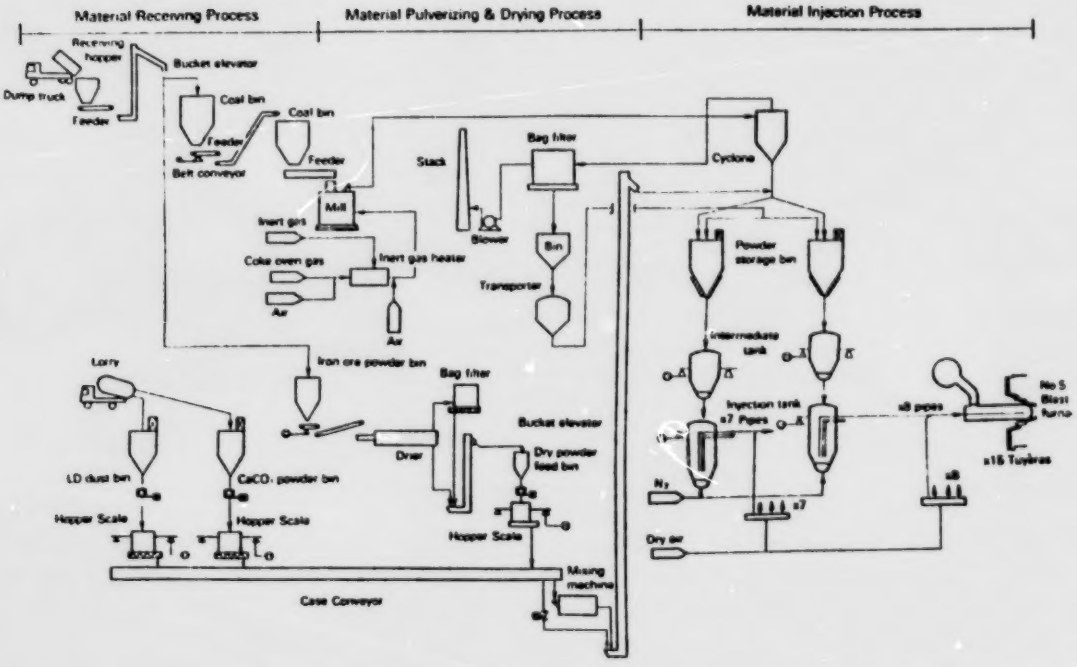


Fig. 26 - Flow diagram of MPI system for Chiba No. 5 blast furnace

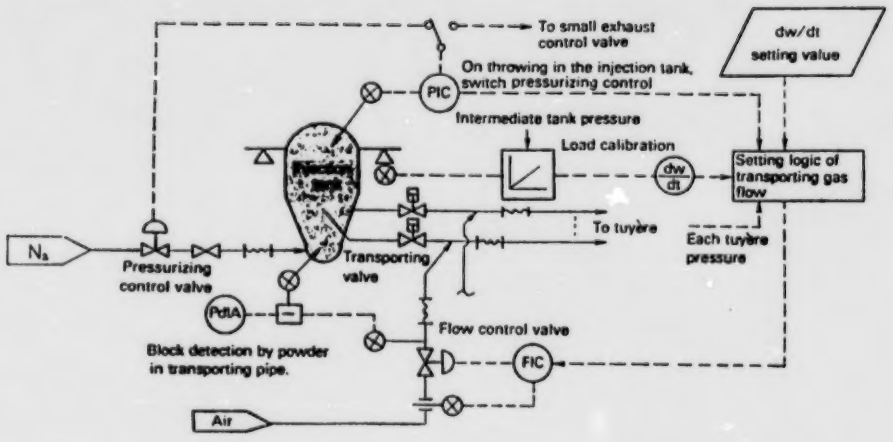


Fig. 27 - Flow chart of powder injection control (Kawasaki Steel Corporation)

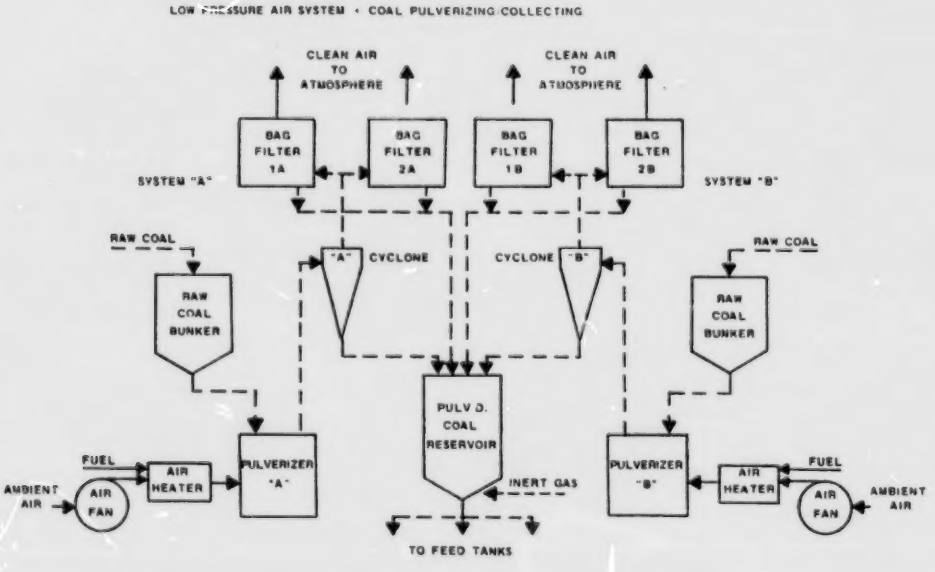


Fig. 28 - Coal flow in ARMCO-Babcock & Wilcox (Amanda) system

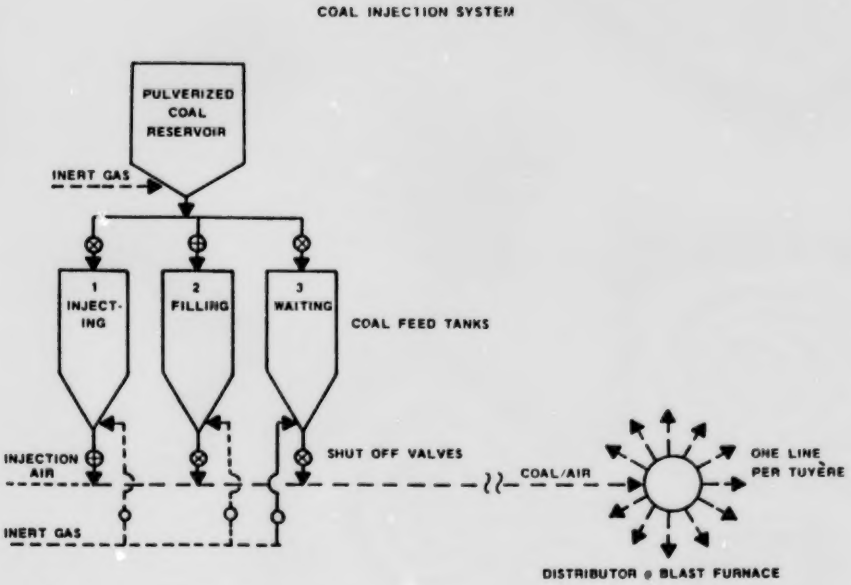


Fig. 29 - Distribution and injection subsystem of ARMCO-Babcock & Wilcox (Amanda) system

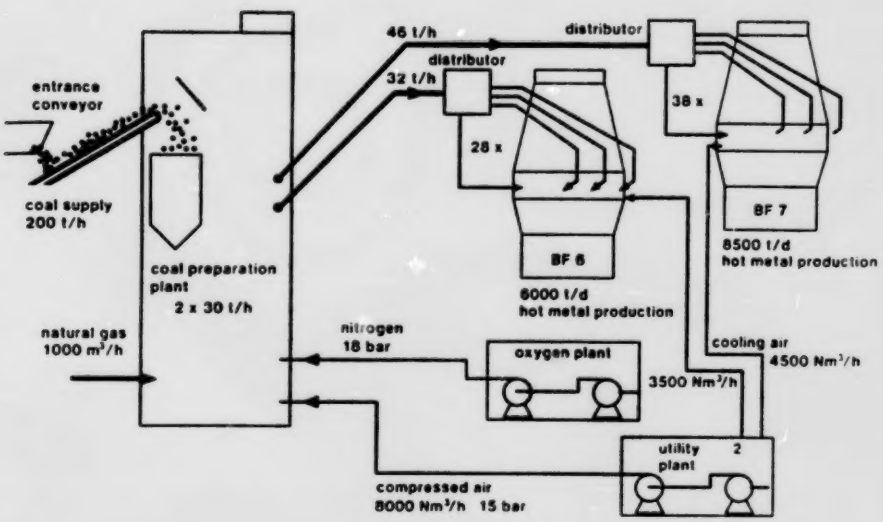


Fig. 30 - Coal preparation, distribution, and injection at Hoogovens Steel Works

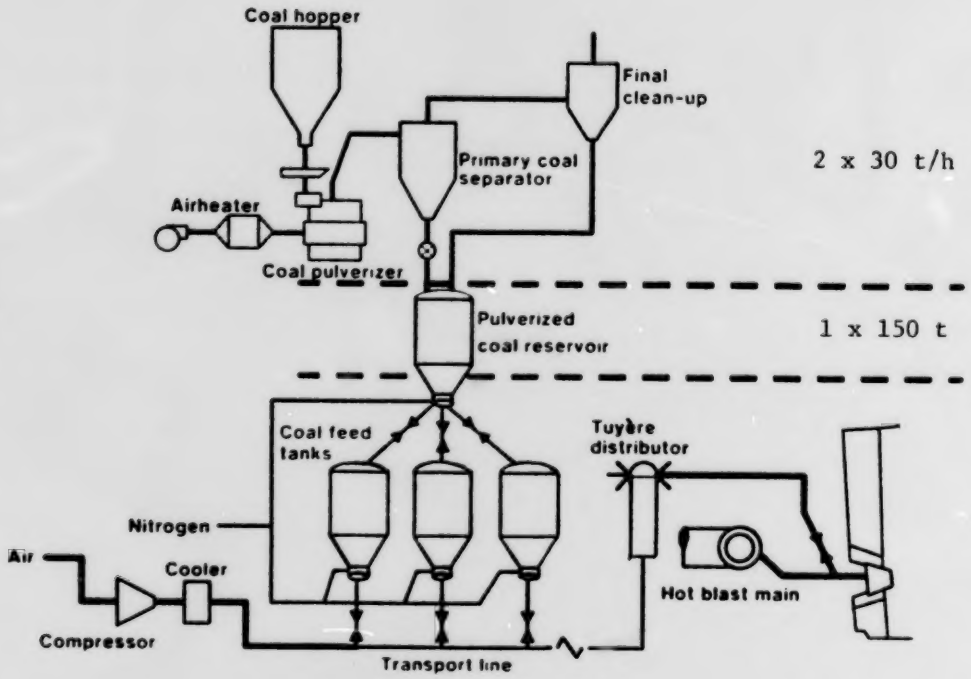


Fig. 31 - Distribution and injection subsystem at Hoogovens Steel Works

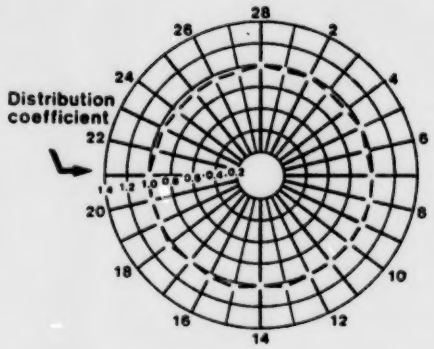


Fig. 32 - Circumferential coal distribution at Hoogovens Steel Works

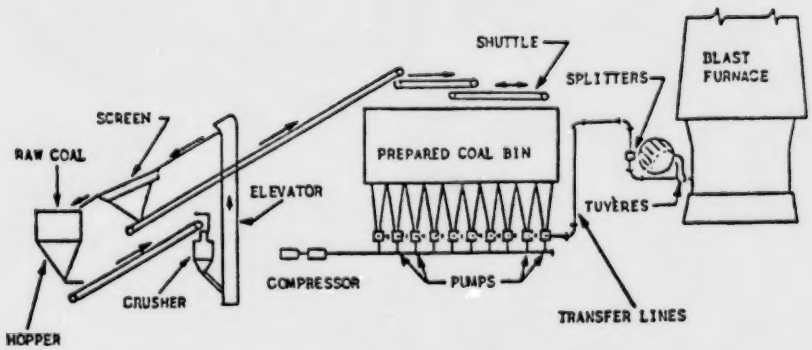


Fig. 33 - Koppers system

This system allows the coal storage bin and feeding equipment to be located at ground level. The heart of the system is the coal feeder (coal pump) shown in Figure 34 (35). A battery of coal feeders is placed under the bin. Coal enters the top of the feeder by gravity flow. Then, the pump rotor moves the coal around to the discharge port where air at high pressure carries the coal into transfer lines. On arrival at the blast furnace, the coal from each feeder is split into two streams, which are fed into two non-adjacent tuyères. The coal rate is controlled by varying the speed of the pump.

KLOCKNER BLAST-FURNACE INJECTION

Both pulverized and granular coal (max. 3 mm) can be injected using the Klockner blast-furnace injection (K-BFI) system (47,48). This system may be applied in different versions (Fig. 35) (48). The K-BFI system of uniform tuyères supply has been applied at Svenska Stal AB, Lulea, Sweden. In the system dependent on differential pressure, the rate of coal injection is controlled by the pressure at the blast tuyère. When this pressure increases at a particular tuyère, a smaller amount of air is blown into this tuyère. It automatically reduces the quantity of coal injected into this particular tuyère. The other tuyères obtain correspondingly more coal. In the other uniform system, the quantity of coal injected remains constant in a similar situation.

ARBED-WURTH SYSTEM

The ARBED-Wurth system (49-52) has been applied at ARBED-Belval blast furnaces, Esh-sur-Alzette, Luxembourg and USINOR, Dunkirk Plant, France. The main features of the installation (Fig. 36) (51) are:

1) Rate of coal injection is optimized:
   - total coal input is a function of the total hot blast flow rate with uniform distribution of coal in tuyères (set point in g/m^3 blast oxygen); and
   - total coal input with the option of varying the quantities of coal injected to each tuyère.
2) Pulverized coal is moved by gravity feed until it reaches the distribution silo.
3) Coal is injected with dried and cooled compressed air obtained from the furnace cold blast line.
4) Feeder silo is equipped with a remote-load cell system to ensure precise control of the amount of coal injected.
5) Safety standards are high:
   - installation is designed to work under with an explosion-proof atmosphere (oxygen below 12%);
   - injection of inert gas (CO_2) into critical zones on receipt of signal from pulverized coal heating detectors; and
   - application of explosion membranes and safety valves.
6) Operation is fully automatic.

MACAWBER-BRITISH STEEL CORPORATION SYSTEM

The granular coal system used by BSC (53,54) is designed to work under gravity, but at times flow initiation is necessary. Experience showed that silos and batch hoppers needed to be filled using aeration systems which have proved successful in avoiding flow problems.

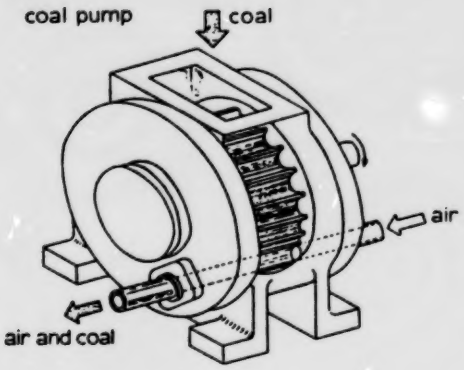


Fig. 34 - Coal feeder

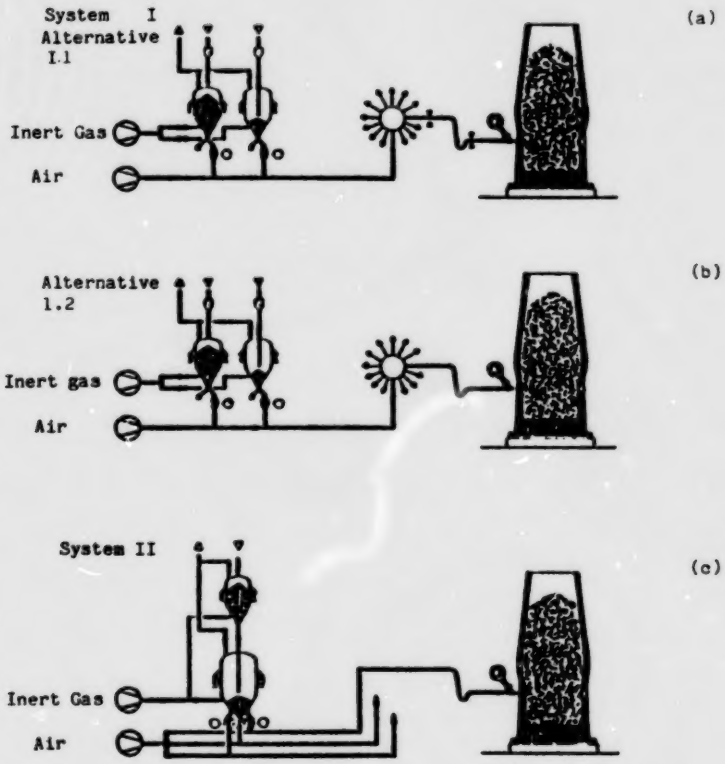


Fig. 35 - Three versions of K-BFI system: (a) uniform tuyères supply independent of Δp; (b) uniform tuyères supply dependent on Δp; (c) individual tuyères supply

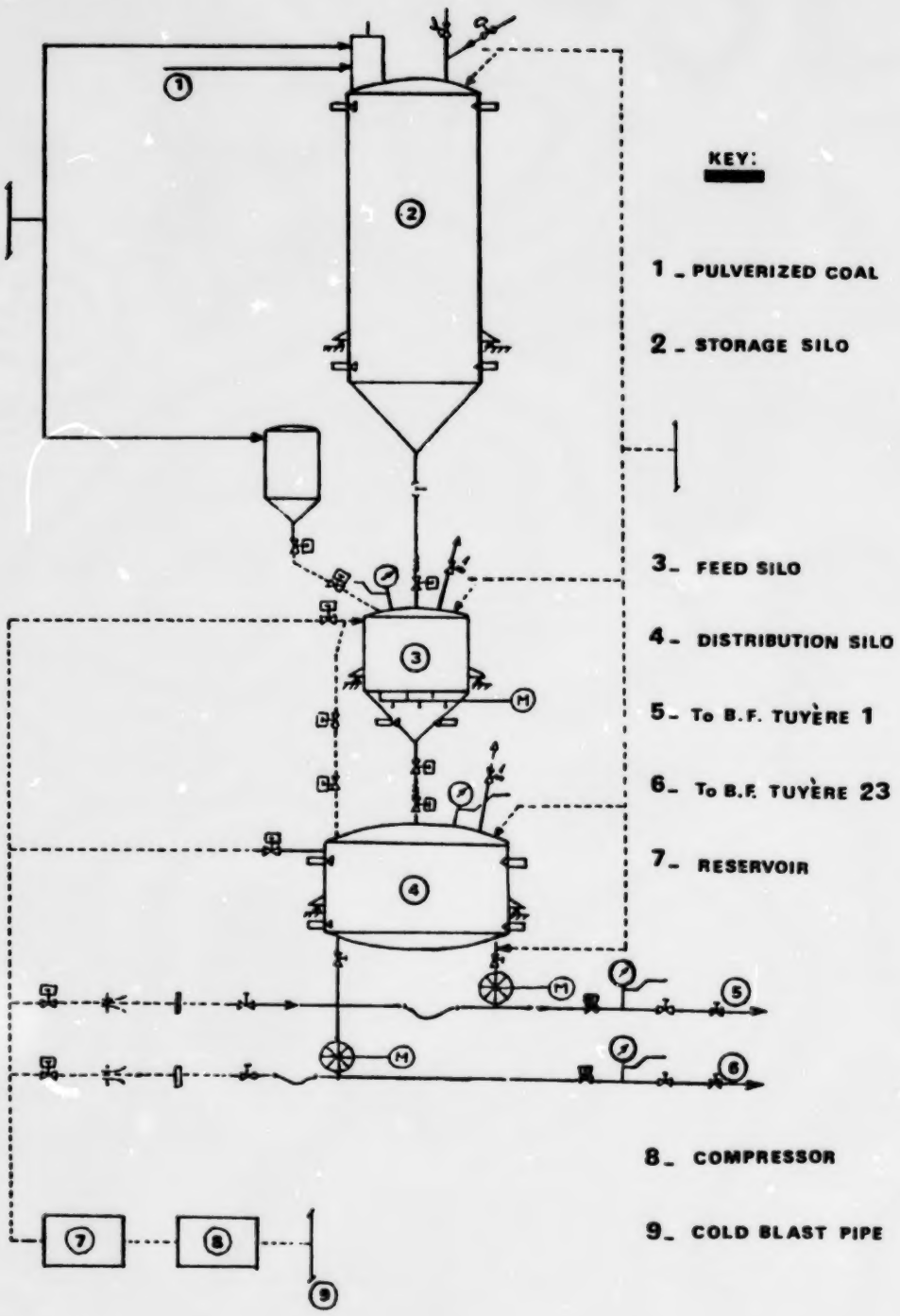


Fig. 36 - ARBED-Wurth system

The injection system consists of 12 injectors per furnace. Coal is conveyed by air from an injector vessel. Each injector feeds two tuyères. One of the injection units is illustrated in Figure 37 (53).

CHINESE SYSTEM

The Chinese system consists of three subsystems (Fig. 38) (15). The injection subsystem is shown in Figure 39 (15). Coal crushed in a ball mill is transferred by pneumatic conveyer to two parallel lines of injection equipment. The upper vessel acts as a lock hopper and the lower vessel as an injection-regulating device. The lower vessel is weighed by load cells and the rate of loss of weight determines the rate of injection. The coal is conveyed using compressed air as the medium of conveyance.

SOVIET SYSTEMS

In the Soviet ironmaking industry (35,56-58), three different systems of coal injection have been used at Zaporozstal, Karaganda, and Doneck. In the Doneck installation (Fig. 40) (56), two consecutive reservoirs (intermediate at label 8, feed at label 9) constitute substantial elements of the system. In the feed reservoir (label 9), a constant pressure is maintained at a level of 0.5 to 1.0 atm above that required to blow coal into the furnace. Six aerated disc feeders (label 10) are attached at the lower part of this reservoir. They ensure an individual supply of a controlled quantity of coal into the furnace through 6 (out of 12) tuyères. The supply through feeders is regulated by varying the number of rpm of the movable disc (from 5 to 15 rpm) (56).

The major disadvantage of the Karaganda system (Fig. 41) is poor accuracy of coal distribution (58).

Another Soviet system applied at Zaporozstal Steel Works is presented in Figure 42 (57). Because of poor distribution of coal, this installation has been modified.

CONCLUDING REMARKS

Two types of systems, pneumatic and mechanical, are used to transport coal to an individual tuyère. At the blast furnace, two operating practices can exist: (a) regular operating conditions in which air is blown in equal quantities to each tuyère; and (b) irregular operating conditions when pressure increases in a raceway at a particular tuyère and less air can be blown into this raceway.

In considering both situations from the viewpoint of coal supply:

- case a requires delivery of equal portions of coal to each tuyère around the furnace, and
- case b requires a lower rate of coal supply to the particular tuyère, otherwise incomplete combustion caused by the reduced oxygen supply may make the situation significantly worse.

A major parameter of pneumatic conveying is a pressure difference between the injection vessel and the furnace. For this reason, pneumatic conveyors are more adjustable to irregular furnace conditions than mechanical feeders. In particular, recently developed pneumatic systems (1, 40, 48) ensure an accurate control of coal supply to individual tuyères in response to pressure fluctuations. However, all pneumatic systems form tall structures and require more space than mechanical systems. Mechanical systems present wear problems associated with handling abrasive coal dust.

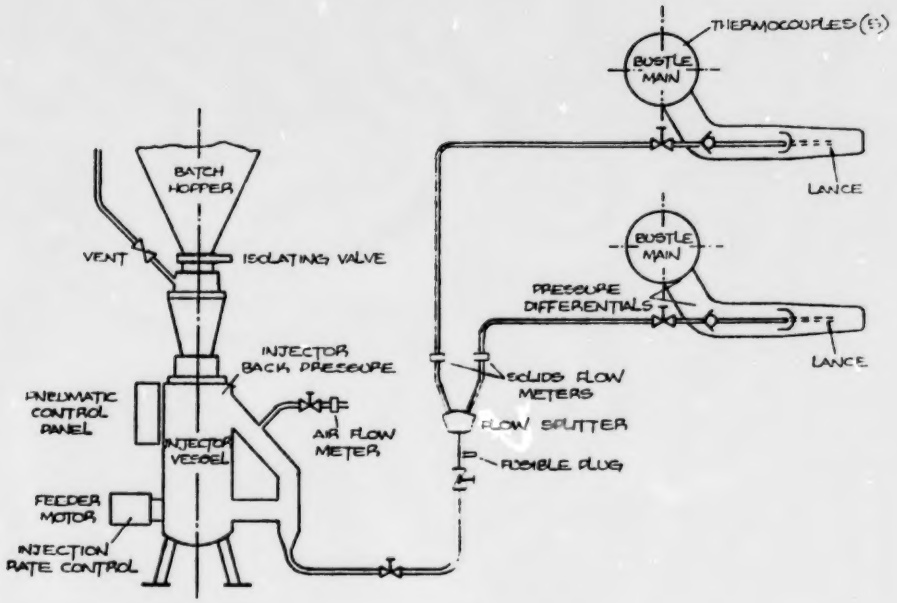


Fig. 37 - British Steel Corporation injection system

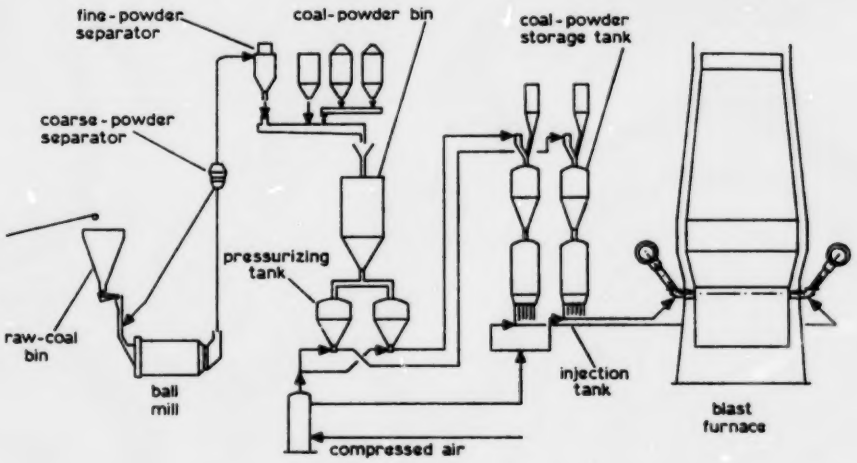


Fig. 38 - Chinese coal preparation, distribution, and injection system

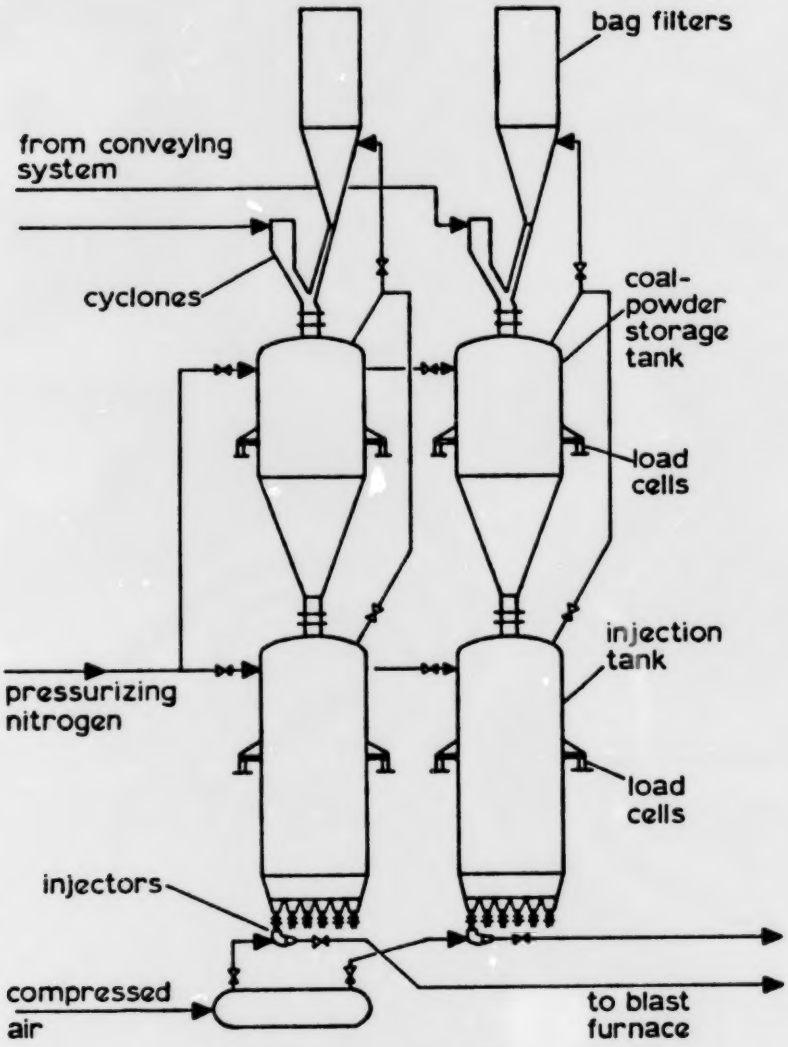
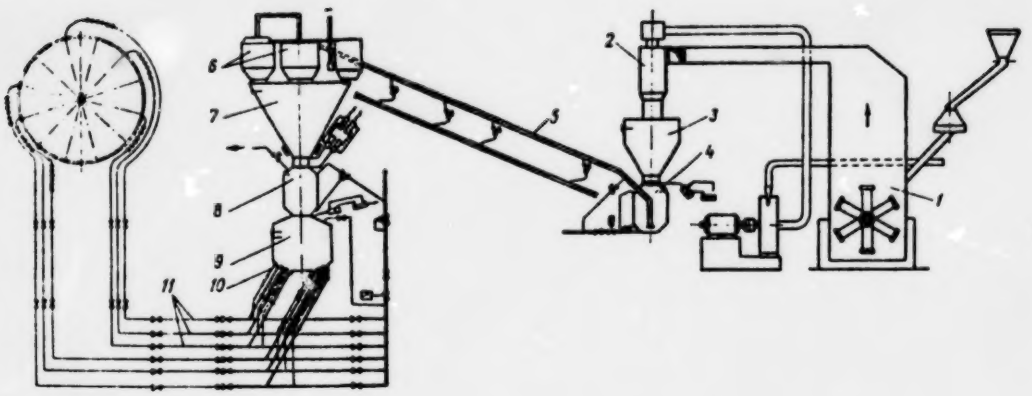


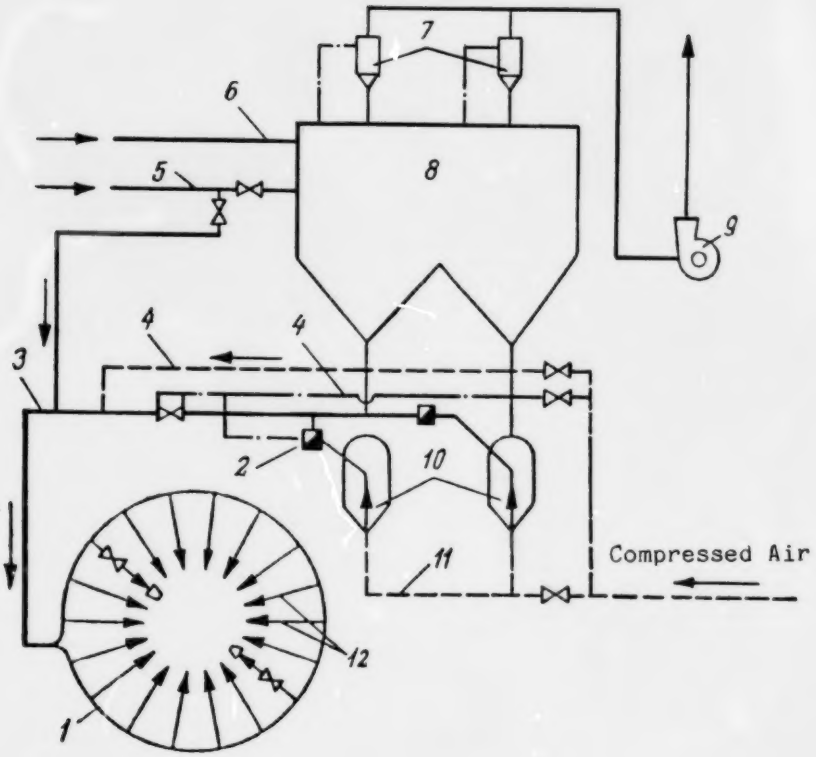
Fig. 39 - Chinese injection subsystem



Legend

1. grinding mill
2. cyclone
3. bunker
4. chamber pump
5. pulverized coal (PC) duct
6. cyclones
7. bunker
8. intermediate reservoir
9. feed reservoir
10. disc feeders
11. ducts distributing pulverized coal (PC) into tuyères

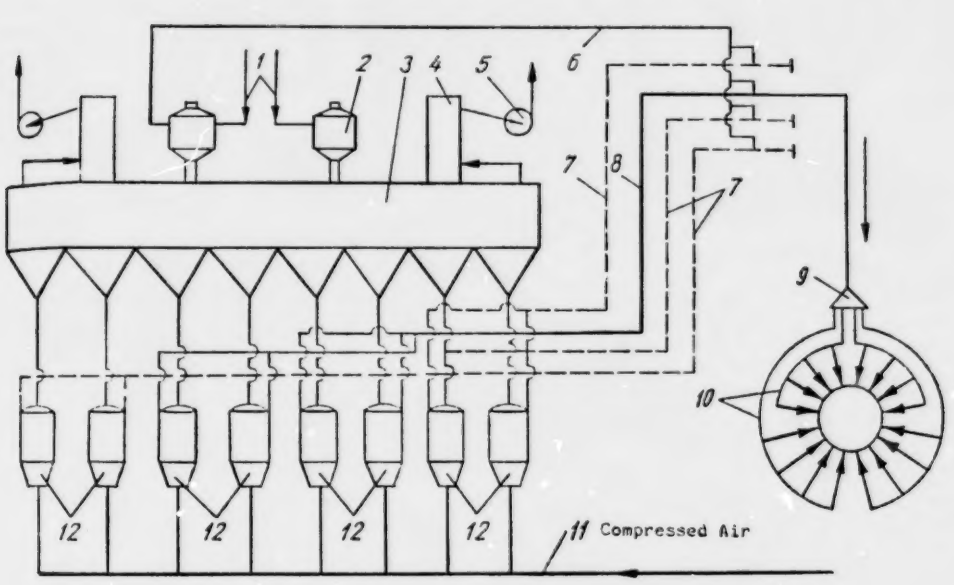
Fig. 40 - Doneck PC1 system



Legend

1. duct distributing pulverized coal (PC) into tuyères
2. valve
3. PC duct
4. duct of compressed air
5. CO_2 inlet
6. PC inlet
7. cyclones
8. storage vessel
9. ventilator
10. two parallel injection vessels
11. compressed air inlet
12. injection tubes compressed air

Fig. 41 - Karaganda PC1 system



Legend

1. PC inlet
2. filter
3. storage vessel
4. filter
5. ventilator
6. recirculation
7. back-up coal ducts
8. coal ducts
9. distributor of pulverized coal
10. duct distributing pulverized coal into tuyères
11. compressed air duct
12. injection vessel

Fig. 42 - Zaporozstal PC1 system

COAL CHARACTERISTICS AFFECTING BLAST-FURNACE INJECTION

COAL CLASSIFICATION

Used in North America, the American Society for Testing and Materials (ASTM) coal classification system is based on proximate and calorific analysis. Coals are often simply classified as being either metallurgical or thermal coal. Thermal coals include non-coking coals, oxidized coking coals and middling and reject coal from preparation plants.

Coal is composed of microscopic constituents called macerals which behave differently under various reaction conditions. Macerals are identified microscopically by their form and reflectivity and are divided into three main groups: vitrinite, inertinite, and exinite. They can also be classified chemically on the basis of their ultimate composition (59).

COAL CHARACTERISTICS

Blast-furnace injection technology is tolerant of a variety of coal characteristics. Consequently, all ranks of coal, from anthracite to lignite have been used in industrial operations (Table 1).

Although different types of coals are acceptable for the blast-furnace injection. their characteristics significantly affect operating results. Such characteristics are: content of hydrogen, volatile matter, sulphur, phosphorus, moisture, and ash; ash composition; ash fusion temperature; and tar yield.

Effect of Hydrogen

Because the combustion of hydrogen provides less energy to the furnace than combustion of carbon, and because the reaction between water and carbon to form hydrogen gas is endothermic, the injection of hydrogen-bearing fuels produces a considerable change in the combustion zone energy balance. As discussed previously, the C:H ratio can be used to characterize the suitability of fuel as an injectant in terms of injection rate and replacement ratio. Data obtained by Ridgion (62) and Cordier (63) presented in Figure 43 (24) show the amount of various fuels that can be injected to compensate for a 100°C increase in blast temperature while maintaining constant RAFT. The larger the C:H ratio of the fuel, the more fuel can be injected.

Table 2 shows the relationship between coal rank and C:H ratio. Note the C:H ratios of the bituminous coals are all quite similar and have similar injection levels as shown in Figure 43.

It can be concluded that fuels with lower hydrogen contents can be injected at a higher rate to maintain a constant RAFT when blast temperature and moisture are kept constant.

Table 1 - Types of coals used for blast-furnace injection

Coal type	Analysis (%) Fixed carbon (FC)	Volatile matter (VM)	Ash	Moisture	S	Ref. no.
Anthracite	83.5	6.0	10.0	0.5	-	(9)
Anthracite	83.0	7.1	8.7	1.2	0.81	(12)
Bituminous	46.5	19.3	33.0	1.2	1.08	(60)
Bituminous	54.4	37.3	4.3	4.0	0.7	(29)
Lignite	41.0	44.0	4.0	11.0	0.5	(61)

Table 2 - Relation of coal rank to C:H ratio

Coal rank	C:H ratio (dry, ash-free basis)
anthracite	30.0
low-volatile bituminous	19.1
low- and medium-volatile	17.8
medium-volatile	16.7
high-volatile A	15.2
high-volatile B	14.2
high-volatile C	14.1

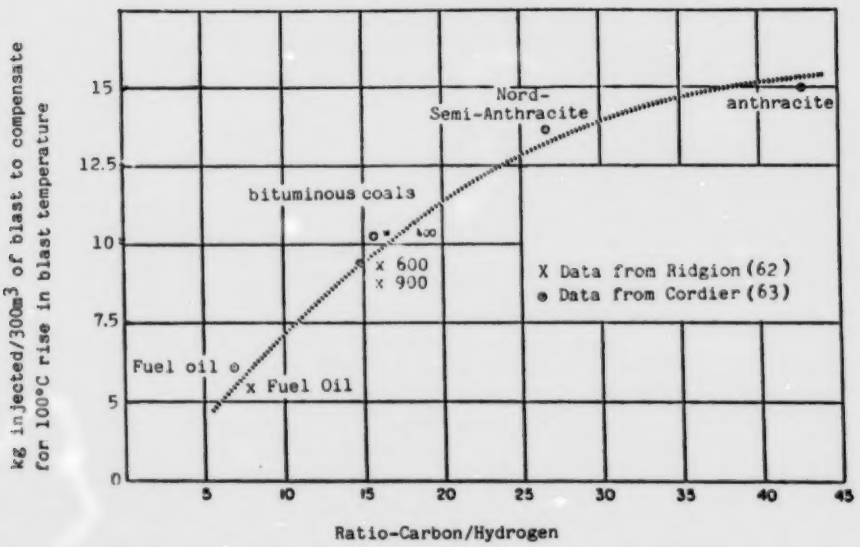


Fig. 43 - Relation of optimum of injected fuel to its C:H ratio

Effect of Volatile Matter

Volatile matter obtained during the pyrolysis of coal consists mainly of combustible gases, such as hydrogen, carbon monoxide, methane, and other hydrocarbons. Heavy hydrocarbons (tar) as well as incombustible gases, such as carbon dioxide and steam, are also part of the volatile matter. Coal rank affects the composition of volatile matter substantially, and the proportion of incombustible gases increases as the coal rank decreases. Maceral composition also affects volatile matter content substantially, and exinite produces more volatile matter than vitrinite which, in turn, yields more volatile matter than inertinite.

Because volatile matter relates to the C:H ratio, as shown earlier, then for maximum injection (and highest replacement ratio) coupled with minimum cooling, a low-volatile coal is desirable. On the other hand, a high-volatile coal is regarded as a fuel with higher combustibility, which is particularly desirable when speed of reaction is an important factor. In general, the coal burnout decreases with increasing coal rank, particularly in the initial stage of combustion (64). Also, the amount and composition of volatile components are important in the undesirable formation of soot under fuel-rich conditions (65,66). The effects of volatile matter and tar yield on combustion efficiency are discussed later.

Effect of Ash

Unlike liquid or gaseous fuels, coal often contains substantial amounts of non-fuel impurities. Ash is the residue derived from the mineral matter during complete incineration of coal. Ash plays an essential role in coal injection because of its content, composition, and fusion temperature.

Washed coals usually have ash contents of 5 to 10%, although values as high as 25 to 30% may occur (60). An increase in the ash content of coal injectants to the blast furnace leads to: (a) an increase in carbon consumption, which reduces the replacement ratio; (b) an increase in flux requirements; and (c) a decrease in production.

Coal ash affects the amount of slag produced in the blast furnace. The quantity of slag produced is also a function of the composition of the ash, the analysis of flux, and the basicity of the slag required to meet metal quality. Usually, 1.5 to 1.86 kg of slag is formed from 1 kg of coal ash. Assuming a carbon coefficient of the slag equal to 0.6, each per cent of coal ash consumes 0.9 to 1.08% of carbon in the coal to produce the slag (24).

Fletcher and Garbee (29), in full-scale trials, related the replacement ratio to the ash content of coal and coke empirically. Both computation and an analysis of operating data (67) confirm the influence of coal ash on the coke replacement ratio (Fig. 44, Table 3).

Ranges for chemical composition of coal ash are:

SiO_2	40-90%
Al_2O_3	20-60%
Fe_2O_3	5-25%
CaO	1.15%
MgO	0.5-4%
$Na_2O + K_2O$	1-4%

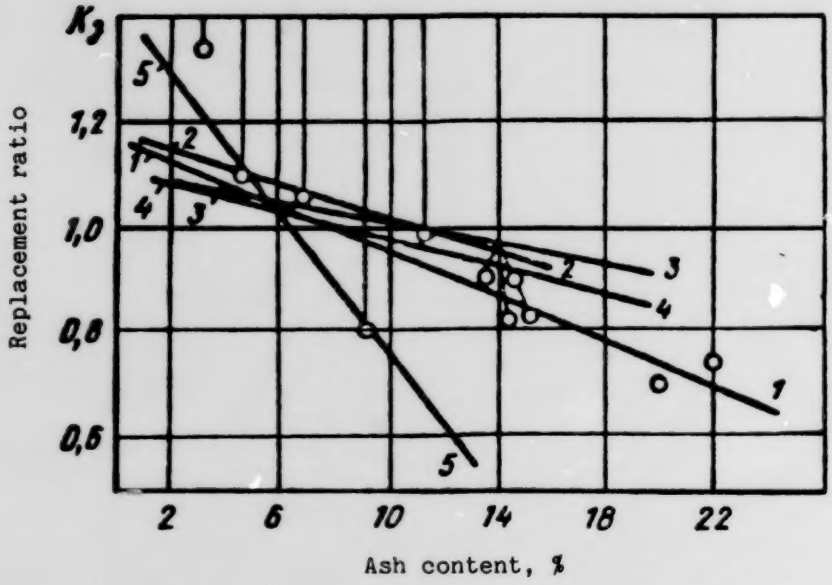


Fig. 44 - Replacement ratio in relation to coal ash content:
1 - experimental data; 2 - calculated by Yaroshewskii;
3 - calculated from carbon balance; 4 - calculated by Ramm;
5 - calculated by Garbee

Table 3 - Relation of replacement ratio to coal type

Company	Replacement ratio	Coal type	Operating conditions
Kobe (Japan)	1.0	32-35% VM 7-10% ash	Blast moisture decreased Injection rate 50 kg/tHM
Stanton (U.K.)	1.0	35.% VM 6% ash	Blast temperature increased Injection rate 74 kg/tHM
British Steel Corporation (U.K.)	0.9	32% VM 4% ash	Granular coal Injection rate 51 kg/tHM
Shoudu Iron and Steel Co. (China)	0.8	Anthracite medium ash	Injection rate 70-120 kg/tHM
	0.7	Anthracite high ash	Injection rate 70 kg/tHM
Karaganda (USSR)	0.6	18% VM 32% ash	Injection rate 50-80 kg/tHM

Most coals, because they contain a mixture of minerals, have a range of fusion points during combustion and can form clinker (a mixture of fused and unfused ash together with unburned carbon). The blast furnace can tolerate coals containing a wide variety of ash minerals because of the high temperature and molten slag but it is preferred if coal ash is compatible with the furnace slag. Ostrowski (68) states that high slag liquidus temperature coinciding with high coal-ash fusion temperature (>1454°C) causes possible solidification of slag or coal ash, or both. To avoid tuyère failure and burden hanging, Ostrowski recommends injecting low-ash coal with low fusion temperature. He also recommends balancing the blast-furnace slag magnesia and alumina to obtain the lowest possible slag liquidus temperature (68).

Slag liquidus temperature is undoubtedly important; however, the ash fusion temperature of the injected coal seems to be less important. Slag from the injected coal ash formed directly in the tuyère zone should trickle into the hearth and have no substantial effect on tuyère failures and gas permeability of the burden.

Effect of Sulphur

Sulphur content of coals may vary from a fraction of 1% to 10% or more and can be either organic or inorganic. Sulphur in an injected coal has the same effect on the sulphur content of hot metal as sulphur entering in materials charged at the top of the furnace. Removal of sulphur is not considered to be a technical problem because blast-furnace slag is a good desulphurizer. Nevertheless, when coal injection increases the amount of sulphur in the furnace, additional costs are incurred associated with increasing slag volume, modifying slag basicity, and/or taking additional desulphurization measures outside the furnace to maintain hot metal chemistry.

Effect of Moisture

A 1% increase in the moisture content of a coal reduces the total amount of coal that can be injected by 1.6 to 2.6% for bituminous coals and about 0.85% for anthracites (24). Also, it is recommended to keep the total moisture below 1% to ensure a smooth flow of pulverized coal during pneumatic conveyance. Coal moisture can be related to inherent coal moisture as shown by data in Figure 45 (23). According to them, pulverized coal moisture increases as inherent moisture of the coal increases.

Effect of Alkalis

Injected coal can be a major source of contamination by oxides of potassium (K_2O) and sodium (Na_2O) in the blast furnace. They are partially reduced to potassium and sodium in the lower part of the furnace, rise to higher parts of the furnace, reoxidize to solid forms, and then descend with the burden. This cyclic process leads to an accumulation of potassium and sodium compounds in the furnace, which restricts gas flow through the burden and increases the reactivity and breakdown of coke by catalyzing the carbon-solution loss reaction. Alkalis also deteriorate the refractory lining in the furnace.

Removal of alkalis by slag requires lowering both basicity and flame temperature, conditions contrary to those needed for low-metal sulphur.

Effect of Grindability

Coals with high grindability would reduce pulverization costs for pulverized coal injection. A relationship between grindability and coal rank is shown in Figure 46 (59). Low and medium bituminous coals are the easiest to grind but this relationship is too approximate to estimate grindability from a coal analysis.

Effect of Particle Size

Coal particle size has been recognized as an important consideration for achieving not only efficient combustion and blast-furnace operation but also economic capital and operating costs. Although pulverized coal gives the greatest opportunity for efficient combustion at the maximum injection rate, coarser coal has many economic advantages. Optimum particle size for injection has not been clearly established but 80% <200 mesh is commonly accepted for industrial systems.

In contrast, British Steel Corporation has successfully practised the injection of granular coal at Scunthorpe (53,54). Experimental units have been operated using three particle sizes: -200 mesh, -1.00 mm, and -3.00 mm.

No major operating problems were observed when granular medium (25%) and high-volatile (37%) coals were applied. Major operating indices and combustion efficiency in both the pilot plant and full-scale operations were comparable to PCI. The granular coal injection rate was in the range of 30 to 76 kg/tHM and the coke replacement ratio of 0.94. The results indicate an economically attractive and efficient technology with the added benefit of relaxing the stringent safety regulations required for PCI systems.

SUMMARY

Commonly accepted coal characteristics for blast-furnace injection may be summarized as follows:

• ash content	<10%
• sulphur content	<1%
• Hardgrove grindability	>40
• desirable ash fusion temperature	<1250°C (68) or <1400°C
• particle size	80% <200 mesh 80%< 2 mm.

Although the fineness of coal is desirable for combustion efficiency, the economical attractiveness of granular coal warrants further investigations to establish the minimum size that will satisfy both combustion and financial requirements.

Content of volatile matter depends on a particular blast-furnace process. Coals with lower contents of volatile matter are preferred for higher rates of coal injection but volatile matter content and composition play an important role in combustion efficiency.

It is worth summarizing the comments of Chinese researchers comparing bituminous and anthracite coal for blast-furnace injection (28).

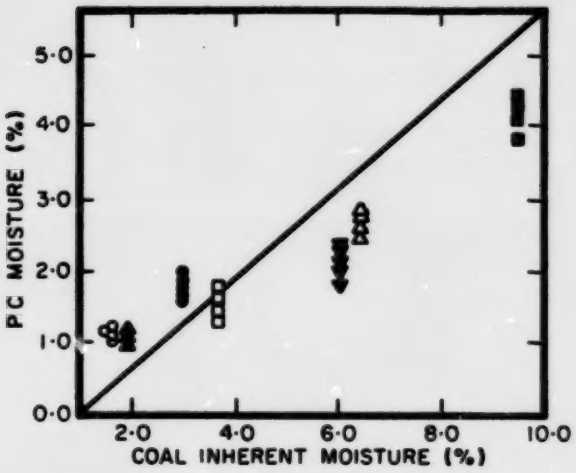


Fig. 45 - Inherent moisture of coal in relation to PC moisture

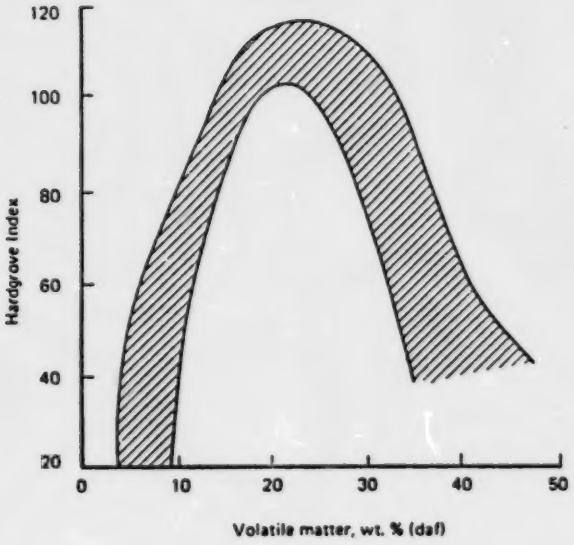


Fig. 46 - Relationship of Hardgrove grindability index with volatile matter content

Safety. The use of pulverized bituminous coal with a spontaneous ignition and an explosive characteristic requires special safety measures such as protective inert gas and temperature monitors. Anthracite injection requires no protective inert gas.

Grindability. The productivity of a ball mill grinding bituminous coal is 13% more efficient than for the same mill grinding anthracite.

Conveying Characteristics. At SISC (China), the velocity of conveying bituminous coal (30% VM) is 25 to 30% higher than that of anthracite.

Maximum Injection Rate. According to Chinese industrial experience, a maximum injection rate of bituminous coal is about 5% lower than that for anthracite.

Replacement Ratio. Contrary to theoretical consideration, the coke replacement ratio of the bituminous coal is about 10% higher than that for anthracite.

COAL COMBUSTION

GENERAL

Combustion of injected coal begins in the blowpipe and ends in the raceway (see Fig. 6). It is important for a solid injectant to be burned within the raceway otherwise it will cause operating difficulties because of reduced burden permeability and an increased coal rate. Unburned coal leaves the furnace along with the top gas and slag. The residence time of a coal particle in the blowpipe-tuyère-raceway system is in the order of 10 ms, much shorter than in other furnaces using pulverized coal. Much research, both experimental (21,34,53,54,64,69-78) and theoretical (69,78-82), has focused on combustion in the blowpipe-tuyère-raceway system. Except for the investigations in the U.K. (53,54), the main stream of research has concentrated on combustion of pulverized coal, i.e., 80% <200 mesh.

PHYSICAL REPRESENTATION

Combustion of coal particles can be described as a multistage process that comprises heating, devolatilization, ignition, gas phase combustion, and heterogeneous combustion. These stages can overlap or can occur in parallel during combustion. Figure 47 presents the stages of combustion of a coal particle injected into the blast-furnace blowpipe. Water and volatile matter are evolved first (phase 1), then carbon monoxide and hydrogen are produced (phase 2) via the water-gas reaction. Within a few thousandths of a second, surface temperature increases sufficiently to ignite (phase 3) and to burn (phase 4) the gaseous coal.

Coal devolatilization (pyrolysis) is an important phenomenon affecting the coal combustion performance (83). Both the amount of volatiles and their composition for a given coal vary with heating rate, duration of decomposition, and final temperature attained. Initially, released volatiles can react with one another or the char that remains. The ultimate yield and composition of the volatiles depend, in part, on the speed with which they are removed from the solid residue.

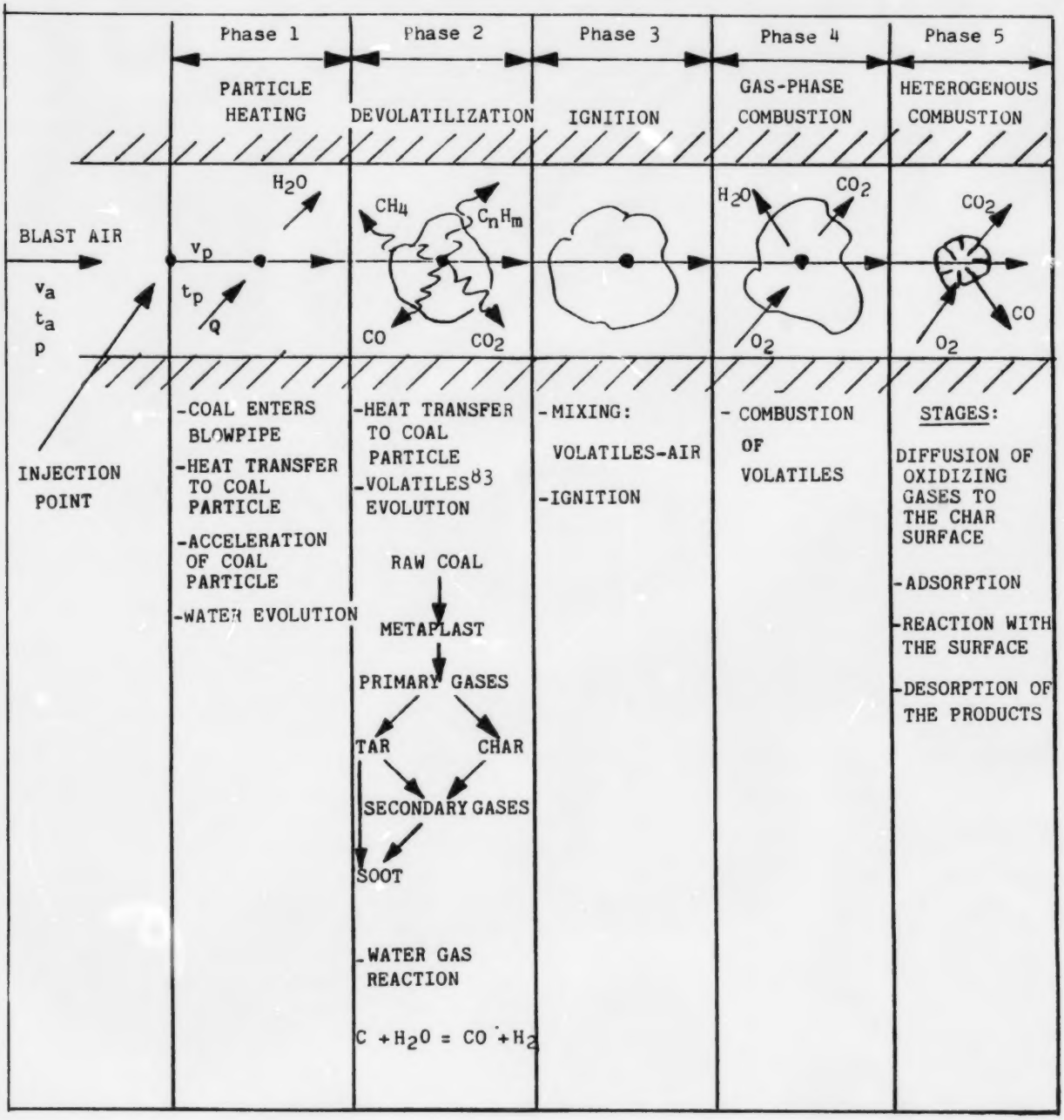


Fig. 47 - Physical representation of coal combustion

Pyrolysis at higher temperature and/or rapid heating rates (10^3 to 10^6°C/s) results in less residual volatiles in the char (84-86) as shown in Figure 48 (84), and produces higher yields of volatiles and tars than for slow pyrolysis or proximate analysis (87).

Figure 49 (84) shows that volatiles liberated in fast pyrolysis have higher C:H ratios than those determined by proximate analysis and that the volatiles released first are richer in carbon than those released later. Coal type also strongly influences pyrolysis products (65,66,88-91) as shown in Tables 4 (84) and 5 (91).

Ignition initiates the gas phase combustion stage of the process. Figure 50 (92) shows the effect of time, blast temperature, and particle size on the surface temperature of a coal.

Ignition temperature depends on the combustible fraction of coal volatiles as shown in Figure 51 (93). After ignition, heat transfer increases considerably which intensifies further devolatilization and combustion.

The simplest model assumes complete devolatilization of a particle before it ignites. Actually, combustion may occur at the surface before devolatilization becomes appreciable but is subsequently extinguished by volatiles, which prevents oxygen from reaching the surface (94). The char remaining after devolatilization consists primarily of carbon, ash and residual volatile matter.

The sequence of char combustion is considered to be as follows:

- diffusion of oxidizing gases to char surface
- adsorption
- reaction with the surface
- desorption of the products.

Heterogeneous reactions of char with the oxidizing gases - oxygen, steam, or carbon dioxide - take most of the time for particle burnout. The rates of carbon oxidation by steam or carbon dioxide are considerably slower than that for carbon with oxygen (84) but, generally, purer forms of carbons are less reactive than char (84). Chars from lower rank coals are more reactive than those from higher rank coals (84). Chars with higher internal surface areas have higher reaction rates.

Table 4 - Apparent products of fast pyrolysis at 1027°C

Coal	Ambient gas	Products, wt %				
		Tar	CH_4	H_2	C_2-C_4	CO and CO_2
Bituminous	Vacuum	<9.9	50.3	13.1	-	26.7
Bituminous	O_2	-	8.0	59.0	-	26.7
Bituminous	Vacuum	53.0	<6.0	<31.0	<3.0	<8.0
Lignite	He	13.0	3.0	1.0	<3.0	38.0

Table 5 - Yields of pyrolysis products for Canadian coals (Fischer assay)

Coal	Products, wt %		
	Tar	Gas	Char
Canmore	0.7	2.6	93.5
McIntyre	3.3	4.8	89.0
Byron Creek	7.0	5.0	82.0
Sukunka	4.9	6.0	86.2
Balmer	5.7	3.9	88.5
Coalspur	8.4	6.1	69.8
Shaughnessey	9.4	6.9	66.6
Devco	13.5	7.4	73.2
Prince	9.9	7.3	72.8
E. Blackfoot	3.2	10.3	64.7
Bienfait *	2.9	11.4	47.4
Onakawana *	3.0	14.2	71.9

* Lignites

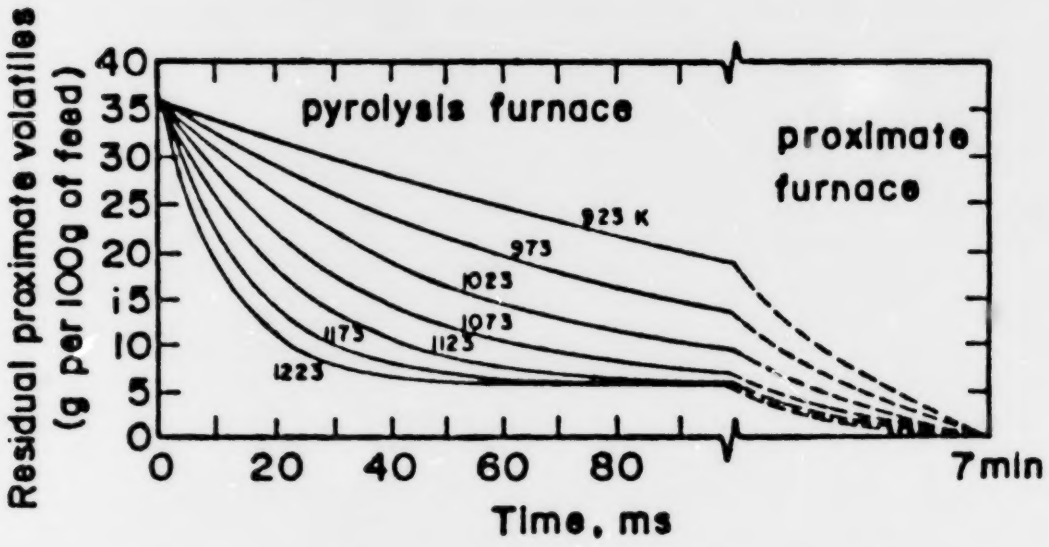


Fig. 48 - Typical devolatilization curves for high-volatile coal at different heating rates

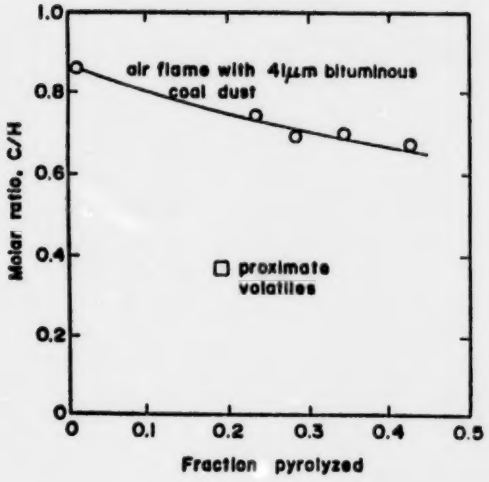


Fig. 49 - C:H ratio vs pyrolyzed fraction

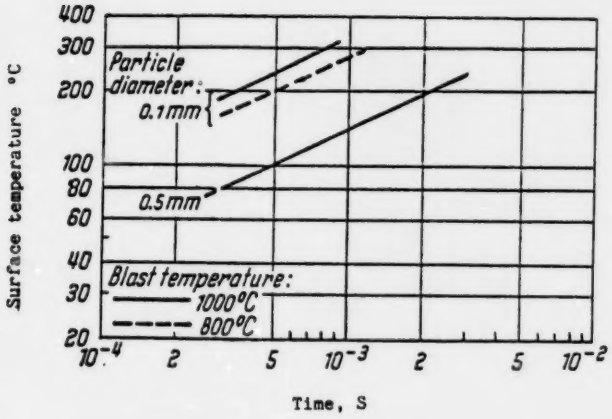


Fig. 50 - Surface temperature in relation to time, blast temperature, and particle diameter

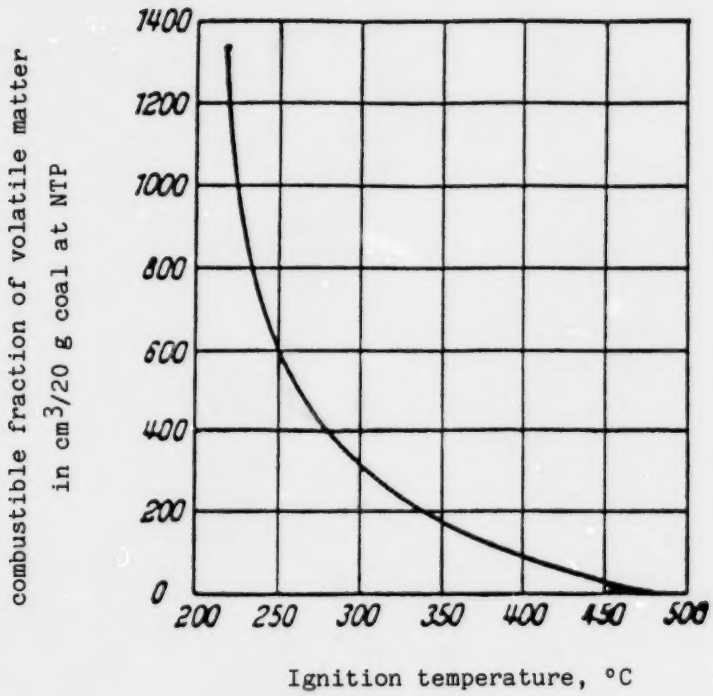


Fig. 51 - Relationship between the combustible fraction of volatiles and ignition temperature

FACTORS INFLUENCING COMBUSTION EFFICIENCY

Location of Injection Lance

Location of an injection point is a significant factor affecting the combustion efficiency (1,19-21,34,68,95). When the injection point is located in the blowpipe, a considerable amount of coal burns in the blowpipe arrangement. The distance from the tuyère to the injection point is a critical factor. Combustion efficiency increases and reaches an optimum when the point of injection is moved upstream. If injection is moved too far upstream, ash deposition can occur in the blowpipe, which impedes gas flow (Fig. 52) (34).

The exact position for injection depends on coal type, blast temperature, particle size, and lance design. At Weirton (National Steel Corp., USA) (68), for example, the location of the injection lance was established 1015 mm from the tuyère for a coal having 39% VM and 5.9% ash.

Coal Type

High volatile coal is considered to have better combustibility than other coals used for blast-furnace injection (34,64,74,78,96,97). Suzuki and co-workers investigated the combustion efficiency of different ranks of coal in an experimental furnace. As shown in Figure 53 (96), they found that the burnout 1.8 m in front of the tuyère was 80% for a low-volatile (20.2% VM) coal and 90 and 95% for two high-volatile coals (33.2 and 39.8% VM, respectively). Nippon Kokan also found better burnout for coals with higher VM when they were injected at rates of 100 to 200 kg/tHM into an experimental blast furnace (3.6 m^3 volume) using blast temperatures ranging from 1000° to 2000°C (98). Results show 96% burnout in the blowpipe for 40% VM coal and 66% burnout for 26% VM coal. Similar trends of combustibility were found by Narita et al. (77).

In other studies, done at International Flame Research Foundation (IFRF) (64,74) in an experimental furnace, the effects of volatile matter (4.1 to 37%), stoichiometric ratio (1.0 to 2.0), blast temperature (933° to 1218°C), and particle size were examined. The following coals were used in this investigation:

P (VM 4.1%; ash 3.9%)
NP (VM 15.9%; ash 10.8%)
ECN (VM 30.9%; ash 6.3%)
AR (VM 37.7%; ash 3.3%).

According to this investigation, content of volatile matter is the most important condition affecting combustion, as shown by burnout and gas temperatures in Figure 54 (64). Differences in combustion behaviour were also found in the appearance of the flame. ECN coal is reported to have a brighter flame (hence containing more soot) than AR coal.

According to Japanese researchers (99), substantial differences in combustion conditions exist between experimental furnaces, such as that discussed above, and a real blast furnace because of the rapid change in temperature and gas composition in the raceway zone and the simultaneous combustion of coke and pulverized coal.

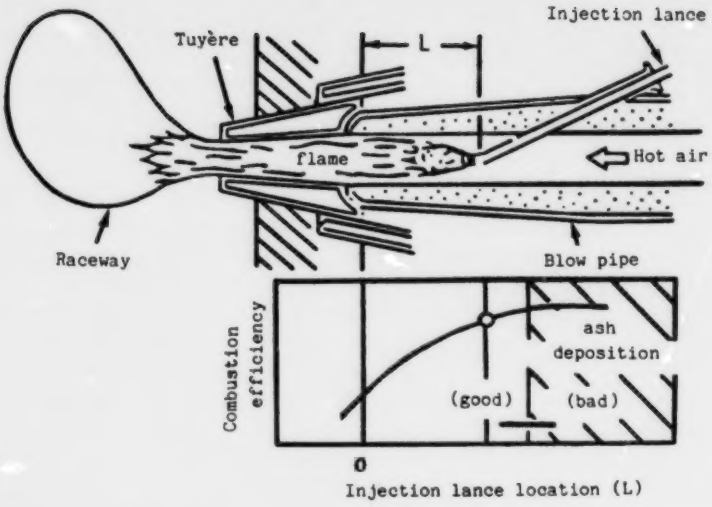


Fig. 52 - Effect of lance location on combustion efficiency and ash deposit

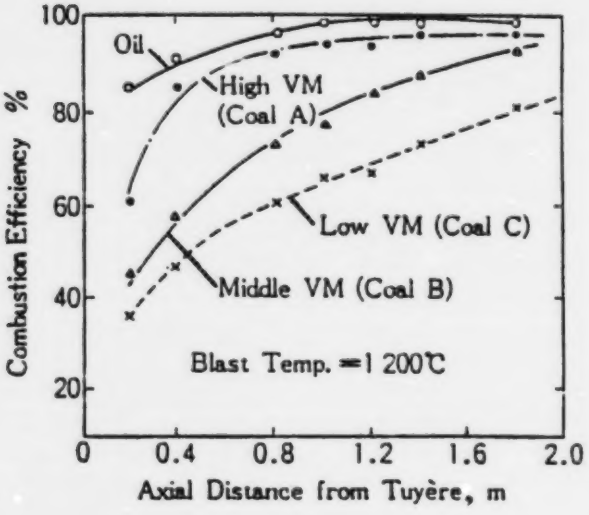
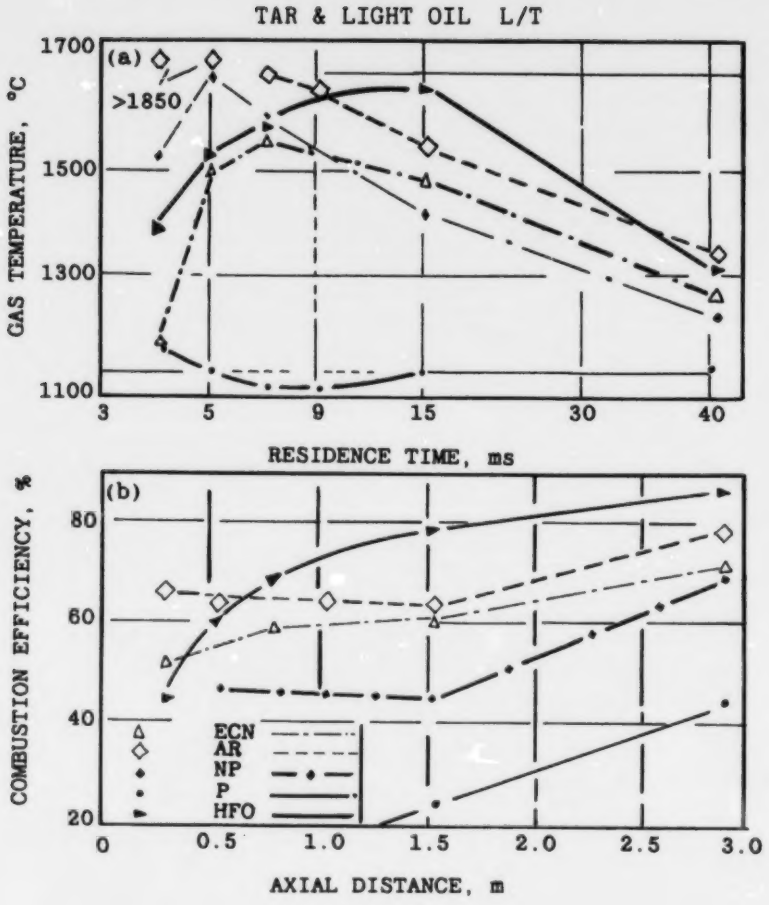


Fig. 53 - Relationship between fuel types and combustion efficiency



Coals tested:

ECN - 30.9% volatile matter
- 6.3% ash

AR - 37.7% volatile matter
- 3.3% ash

NP - 15.9% volatile matter
- 10.8% ash

P - 4.1% volatile matter
3.9% ash

HFO - Heavy Fuel Oil tested

Fig. 54 - Variation of combustion parameters with injected fuel

Based on analysis of coal samples taken from Chiba Works, it has been suggested that final combustion efficiency in a blast furnace depends more on the char combustion than on the gas phase combustion (99).

Stoichiometric Ratio/Injection Rate

The stoichiometric ratio is the ratio of air actually supplied to air theoretically required to burn coal completely to carbon dioxide, water, and sulphur dioxide. Published works (19,21,75) report empirical relationships between combustion efficiency and coal injection rate, which, in its nature (blast volume constant), relates indirectly the combustion efficiency to stoichiometric ratio. However, consideration of combustion efficiency versus coal injection rate gives no information about combustion conditions unless blast volume is known. Without complete information, it is difficult to analyse and compare many combustion systems reported in the literature.

Figure 55 (21) presents experimental findings for three coals of different volatile matter content (coal A, 36.7% VM, C, 17.7% VM, D, 5.7% VM) relating the combustion efficiency to the coal injection rate with the blast volume constant. Figure 55 shows that an increase in the coal injection rate, which for the same blast volume reduces the stoichiometric ratio, decreases the combustion efficiency. Further experimental proof that the higher stoichiometric ratio results in an enhanced burnout is provided by data presented in Table 6 and other publications (19,75). Table 6 shows that changing the stoichiometric ratio changes the burnout after downfield combustion more than at an earlier stage of combustion (64).

Blast Parameters (Temperature, Pressure, Oxygen Content)

Experimental studies in several countries show increased amounts of coal burnout with higher blast temperature (1,64,74,75,96,98,100), blast pressure (76), and oxygen content (64,74,75). Figure 56 shows that oxygen enrichment enhances combustion efficiency (75). The influence of blast temperature is evident in the range of 1000° to 1100°C (Fig. 57) (1). Figure 58 (76) shows that increasing blast pressure promotes combustion markedly up to 3 kg/cm^2.

Particle Size

A small particle size is more effective in increasing the combustion rate (1,35,74-77) as shown in Figure 59 (1). Bortz (74) reports that the use of a finer particle size has little effect on the devolatilization process but that it enhances the char combustion stage at which small coal size results in a faster burnout. For a low stoichiometric ratio of 1.0, a finer particle size is not beneficial until the particle has moved about 1.5 m from the injection point (char combustion region). But for a stoichiometric ratio of 2.0, the effect is observed closer to the injection point (74).

The consensus is that finer coal burns quicker and more effectively than coarser coal and all ironmakers, except British Steel Corporation, use pulverized coal (80% <200 mesh). According to British reports (53,54), the use of a granular coal (98% <2.0 mm) allows them to achieve operating and combustion efficiency comparable to that of pulverized coal.

Table 6 - Experimental conditions

Flame no.	Blast temp. °C	Blast rate, kg/h	Blast velocity, m/s	Fuel type	Fuel rate, kg/h	Stoichiometric ratio	Blast O_2,%	Burnout 1.0 m (10 m/s)	Burnout 1.5 m (15 m/s)
F13	1164	2977	211	ECN*	290	0.98	21.5	--	59
F15	1185	2841	205	ECN	290	0.94	21.0	--	62
F25	1188	2978	213	ECF**	280	1.02	21.2	54	61
F22	1030	3335	216	ECN	310	1.03	21.3	64	63
F40	1012	3367	214	ECN	300	1.08	23.0	61	64
F18	1177	3058	220	ECN	140	2.10	21.3	61	77
F26	1179	3033	217	ECF	150	1.94	21.2	74	81
F23	1011	3332	213	ECN	150	2.14	21.1	60	72

* Elk Creek coal, normal grind.
**Elk Creek coal, fine grind.

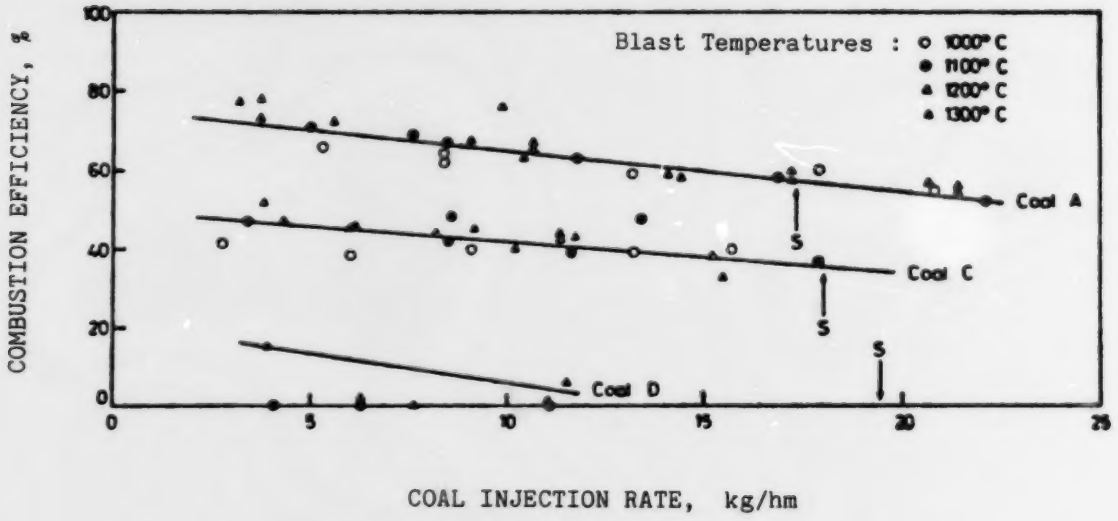


Fig. 55 - Combustion efficiency as a function of coal injection rate

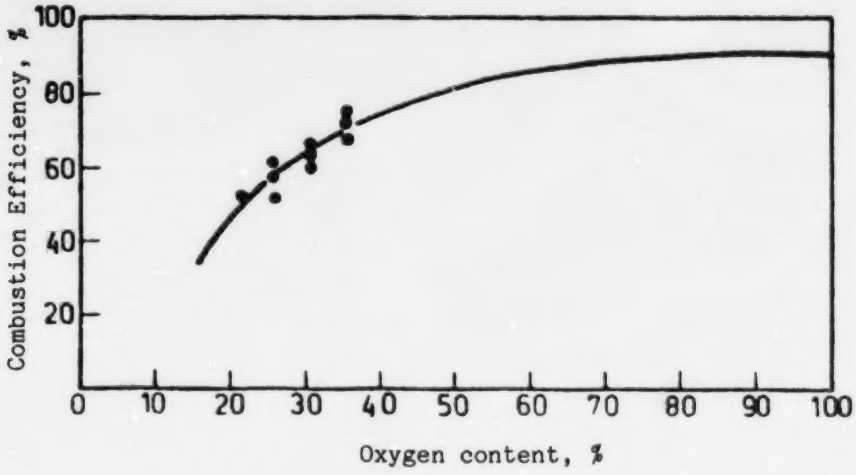


Fig. 56 - Relation between oxygen content in blast and combustion efficiency

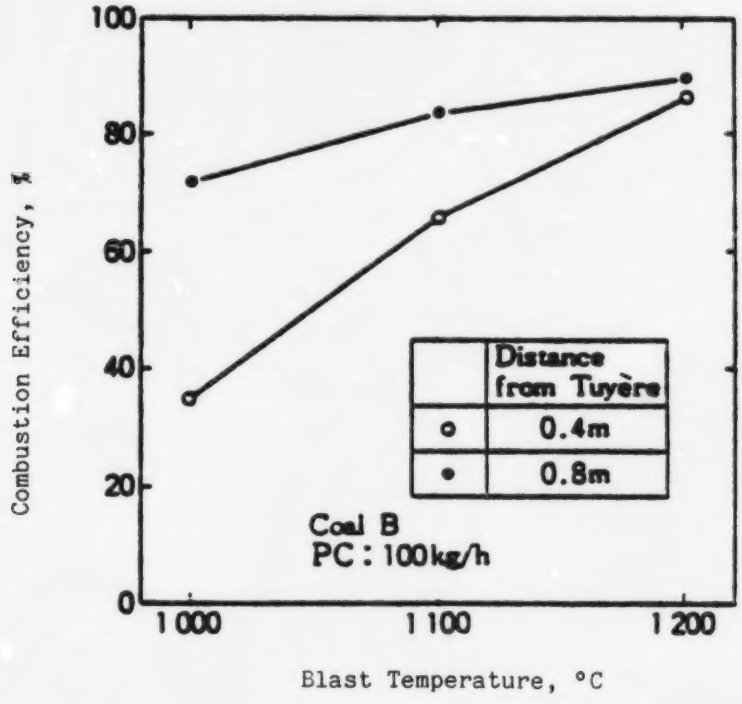


Fig. 57 - Combustion efficiency in relation to blast temperature

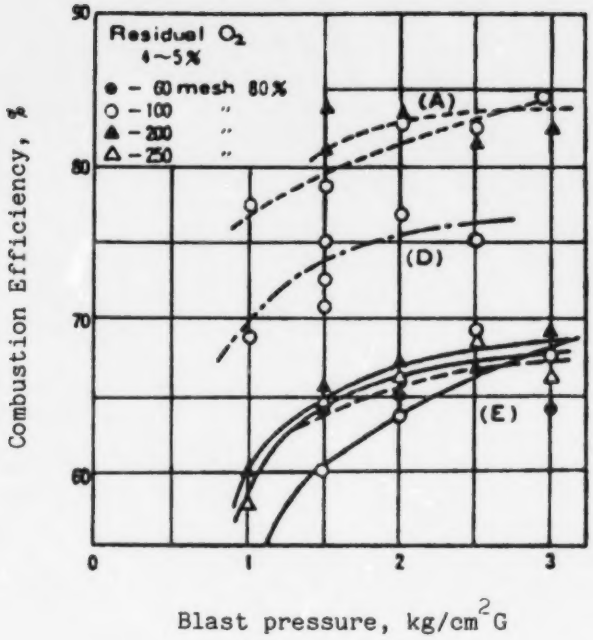


Fig. 58 - Combustion efficiency in relation to blast pressure

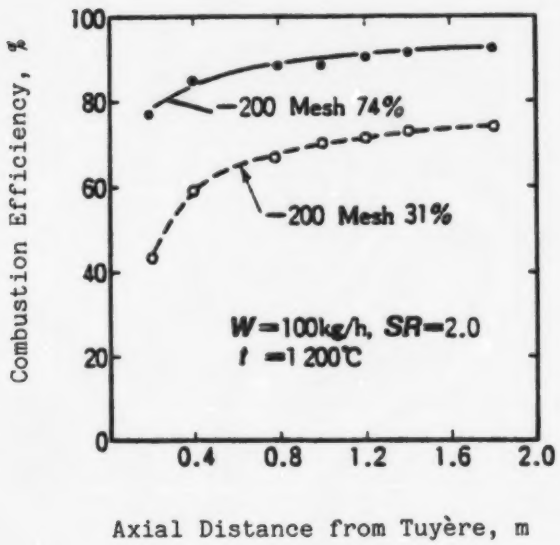


Fig. 59 - Relation between combustion efficiency and particle size

Maceral Composition

Coal combustion characteristics are often attributed to maceral composition (101-105). In particular, a high content of inert macerals has been related to a higher level of unburned carbon (101,103). A different combustion behaviour is observed in the devolatilization and gas-phase combustion when vitrinite-rich bituminous coal is burned. It has a larger apparent volatile matter loss and higher combustion efficiency than that of the inertinite-rich coal (104). Char combustion rates of these coals are observed to be similar (104).

MATHEMATICAL MODELS

Mathematical models have been developed to evaluate and predict the optimum blast furnace injection conditions (78-81). In a model established by Burgess et al. (78), the evolution of volatile matter, combustion of volatiles, and char combustion are considered as separate processes. This model simulates the fuel-lean combustion of pulverized coal in the blowpipe of a blast furnace.

Another mathematical model developed at Newcastle University, Australia, (79) extends the combustion process to include the blast-furnace raceway. This model predicts the effect of changes in injection rate and the use of various types of coal, both high- and low-volatile coals. Formulation of this model consists of particle heating, particle velocity, coal devolatilization, heterogeneous reactions, reaction at a coke bed, mixing and combustion in the gas phase, gas temperature, and composition.

Nomura and McCarthy (80) have developed a model of pulverized coal combustion in the blast furnace assuming:

- two-zone physical representation (warm-up and burning);
- adiabatic, one-dimensional flow system; and
- uniform distribution of coal particles across the blowpipe cross section.

Their model defines: (a) position of a particle at time t in the blowpipe (for warm-up zone); (b) time that a particle requires to be ignited; (c) time that a particle requires to reach the tuyère outlet; and (d) combustion rate. This model was used to predict combustion rates for various coals.

Major conclusions of these theoretical models are fourfold:

1) Temperature of gas in the blowpipe increases as a result of combustion; gas temperature curves, after an initial sharp increase because of devolatilization and gas-phase combustion, start to plateau when heterogeneous combustion dominates; temperature profiles of high-volatile coals increase more quickly than low-volatile coals, particularly at higher injection rates.

2) Coal burnout is higher for coals having more volatile matter.

3) Combustion efficiency is dramatically affected by changes in blast temperature; the higher the initial temperature, the higher the combustion efficiency.

4) Degree of burnout decreases as the coal injection rate increases.

Results from mathematical models do not always agree with combustion results from experiments on operating blast furnaces (99). In the model of Burgess et al. (78), for example, the combustion efficiency increases with increasing injection rate. Also, the mathematical models treat volatiles as non-decomposable matter whereas it has been experimentally proven that decomposition of volatiles takes place during combustion. As a result, tar and soot are produced which affect combustion efficiency and final degree of burnout (as discussed later).

SUMMARY

The combustion efficiency of coal injected in a blast furnace may be increased:

by increasing:
- stoichiometric ratio
- blast temperature
- blast oxygen content
- blast pressure (up to 300-400 kPa); and

by reducing:
- coal size
- coal injection rate in connection with constant blast volume.

A high content of volatile matter (low C:H ratio) has been regarded as a factor promoting high combustion efficiency, particularly in the gas-phase combustion stage. However, the completeness and rate of combustion are controlled by heterogeneous combustion reactions. Not only is combustion affected by the amount of volatiles but also by the composition of the pyrolysis products, particularly tar. Thus, volatile matter is not the only important property affecting coal combustibility and a new approach for assessing coal for injection purpose is required.

NEW ASPECTS OF COAL EVALUATION FOR BLAST-FURNACE INJECTION

Several factors affect coal combustibility. Results from the literature indicate that coal tar yield is important in evaluating coal for blast-furnace injection.

COAL COMBUSTION, TAR, AND SOOT FORMATION

Important coal characteristics for blast-furnace injection are: hydrogen content, volatile matter content, ash content, ash composition, ash fusion temperature, moisture content, sulphur and phosphorus content, alkali content, and tar yield in pyrolysis products. The effects of coal components such as

hydrogen, ash, moisture, alkalis, and sulphur on overall performances of blast furnaces are clearly recognized. However, coal properties affecting combustibility are of primary importance because of the particularly short residence time and low stoichiometric ratio of air to coal for combustion at high injection rates in the blowpipe-tuyère-raceway system (Fig. 60).

According to the criterion most commonly accepted by blast-furnace engineers and operators, the higher the volatile matter (30-40%) of an injected coal, the more efficient is combustion. This viewpoint is reflected in many publications (20,34,43,68). We question whether this criterion alone is sufficient to characterize coal combustibility in blast furnaces and suggest that the tar yield should also be considered. Combustion of the high-volatile coals is markedly more rapid than for other coals during the initial stage of the process, because they quickly produce large amounts of volatiles. Rapid devolatilization results in a higher degree of burnout in the blowpipe and a sharp increase in the flue gas temperature in the blowpipe (see Fig. 54). However, other experiments have shown that particle temperature for low-volatile coal can exceed that of higher-volatile coals near the end of the blowpipe, suggesting that heterogeneous combustion becomes the controlling factor as the process proceeds (see Fig. 60) (97). Also, Figure 54 shows the final degree of burnout for a low-volatile coal (NP, 15.9%) is about 70%, which is comparable to 72% found for a high-volatile coal (ECN, 30.9%) and confirms that coal combustion in the blast furnace is controlled by heterogeneous combustion.

Results obtained by several workers (88,91,106) indicate that tar yield is related to the volatile matter content of the coal. Tar and light oil yields produced from various coals under conditions of Fischer assay pyrolysis are plotted versus proximate volatile matter in Figure 61 (107). Maximum yields occur for high-volatile bituminous coals. Experiments of Loison and Chauvin (88) done at 1100°C (similar to hot blast temperature) also suggest that maximum tar yield is produced by coals in the high-volatile bituminous range (Fig. 62) (64). In general, the yield and composition of tar depend on temperature of reaction, residence time, coal type, heating mode, and immediate environment (presence of some inorganics and/or gas atmosphere). Devolatilization in the blowpipe-tuyère proceeds at a very fast rate of heating that not only increases tar yield but also its C:H ratio (107). Tar produced in coal pyrolysis forms soot during combustion. It has been estimated that in the temperature range 1600°-2000°C almost one-third of the mass of volatiles is transformed to soot (108). Carbon particles (soot) have a graphite-like structure consisting of crystallite spheres or chains, which, at high temperature, become a source of luminous radiation (109). Beer, in a study of coal flames, observed higher radiation from the flame of pulverized bituminous coals than from pulverized anthracite, which indirectly confirms the results of Figure 40, namely that coals having higher contents of volatile matter have increased formation of tar and hence soot (110).

Tar and soot are undesirable materials in a blast furnace. Soot has few surface pores and no internal surfaces available for heterogeneous reactions. As such, it is less reactive than char (84) and complete combustion demands a high air:fuel ratio and a long residence time not available in the coal injection process. Formation of soot can cause an increased fuel rate and many serious operating problems, such as blockage of raceways, decreased burden permeability, undesirable temperature distributions within the furnace, and hanging and rolling of the burden.

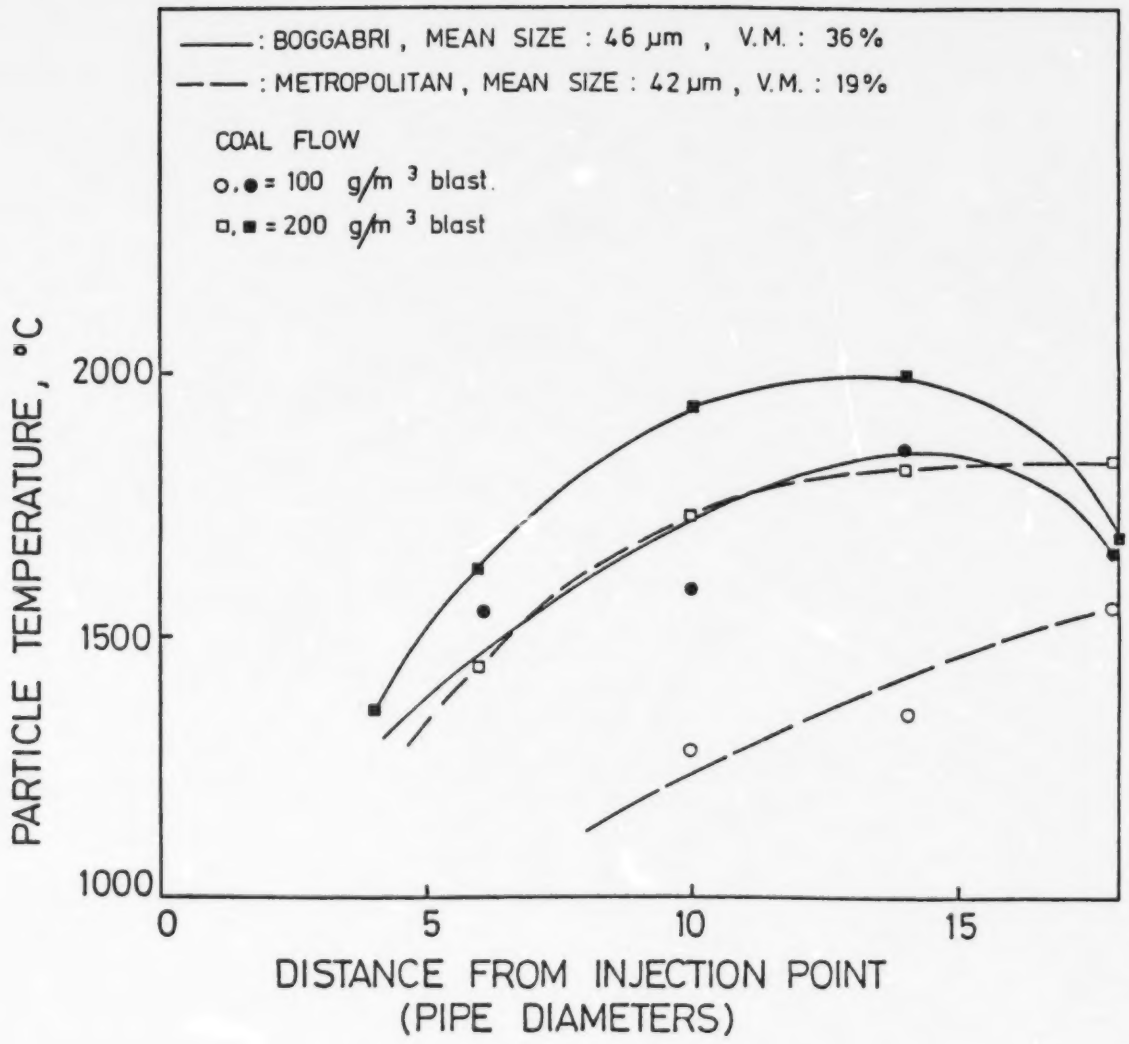

——: BOGGABRI , MEAN SIZE : 46 µm , V.M. : 36 %
— — : METROPOLITAN , MEAN SIZE : 42 µm , V.M. : 19 %
COAL FLOW
o, ● = 100 g/m 3 blast.
□, ■ = 200 g/m 3 blast
PARTICLE TEMPERATURE , °C
2000
1500
1000
0
5
10
15
DISTANCE FROM INJECTION POINT
(PIPE DIAMETERS)

Fig. 60 - Combustion characteristics of medium- and high-volatile coals

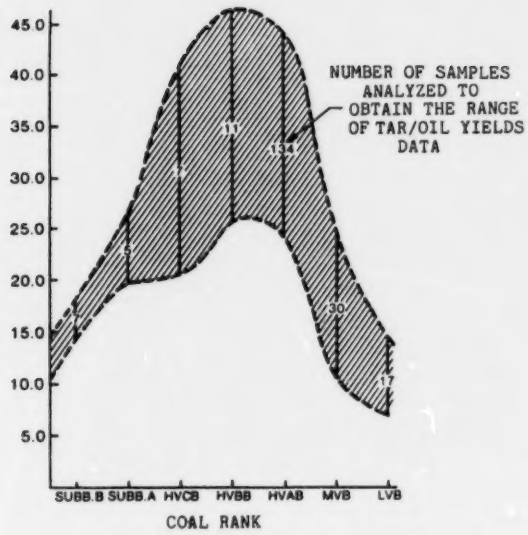


Fig. 61 - Influence of coal type on tar yield (Fischer assay)

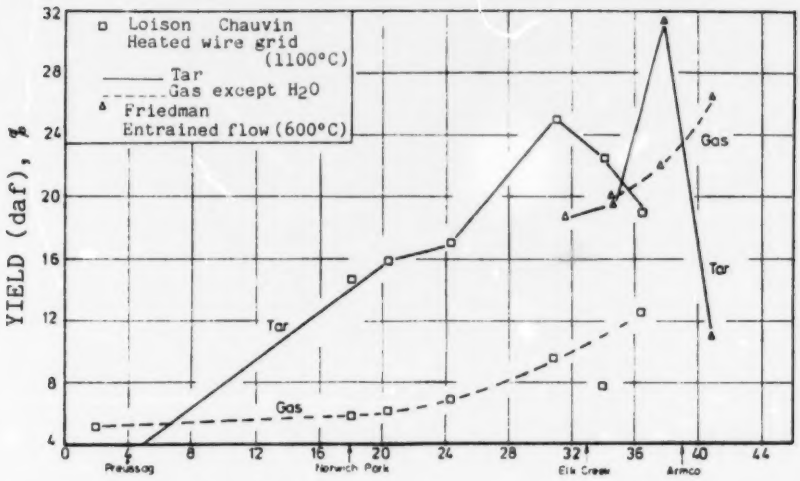


Fig. 62 - Pyrolysis products vs proximate volatile matter content

Kawasaki Steel Corporation recently conducted a combustion investigation based on a newly developed probe installed at No. 5 blast furnace at Chiba Works (99). Combustion efficiency was determined by classifying samples into five colour indices. Samples were taken from the raceway of an operating blast furnace and measured for darkness. An index of 1 represented a grey colour taken on the furnace without PCI and the maximum colour index of 5 represented the darkness of graphite powder. Figure 63 shows that, as the PCI ratio was increased, coal B with 22.8% volatile matter exhibited a smaller change in the colour index than coal A with 34.3% volatile matter. For example, at a PCI ratio of 60 kg/tHM, coals A and B displayed colour indices of about 4 and 2 respectively, demonstrating there was more unburned carbon in the raceway when coal A was injected. Because the burnouts cannot be interpreted on the basis of volatile matter content of the coals, it is probably attributable to differences in their tar contents, with coal A producing more tar (hence soot) in accordance with Figures 61 and 62. Results in Figure 63 and other relevant studies (64-66,88,106,111-114) indicate qualitatively that low tar yield and high stoichiometric ratio of air to coal are major factors influencing efficient coal combustion. These results imply that coal tar yields must be considered as a significant factor in the evaluation of coal for blast-furnace injection. Thus, a knowledge of the volatile matter content alone is insufficient to characterize coal combustibility and its affect on blast-furnace operations.

CONCLUSIONS AND RECOMMENDATIONS

Tar yield should be considered in coal selection procedures for blast-furnace injection as it is a significant factor influencing combustion efficiency. It affects combustion efficiency of coal, particularly in conditions of low stoichiometric ratio, by producing soot, which has poorer combustibility properties than chars. These heterogeneous reactions determine the final degree of coal combustion more than the gas-phase reactions that occur earlier in the blowpipe-tuyère-raceway system.

High-volatile coals have the potential of bearing undesirably large amounts of tar. Coals with low tar yields and perhaps reduced volatile matter may have optimum combustion performance for injection into blast furnaces. Coals with lower volatile matter have higher C:H ratios and would improve the coke replacement ratio. Currently, potentially good medium- and low-volatile coals may be overlooked for injection purposes because selection for combustibility is based solely on volatile matter content.

Methods to reduce tar production from all coals during injection should be considered. In particular, the influence of calcium oxide on pyrolysis products and combustion efficiency in blast-furnace conditions requires further investigation because it has been shown to increase significantly the yield of hydrocarbon gases, hydrogen, and carbon monoxide while reducing liquid yields (107,115,116).

Further investigations using blast-furnace injection conditions are required to describe quantitatively the influence of tar yield on combustion efficiency for coals of different rank and ash contents. Also, more information about the char combustion in the blowpipe-tuyère-raceway is needed for a better understanding and optimization of the process.

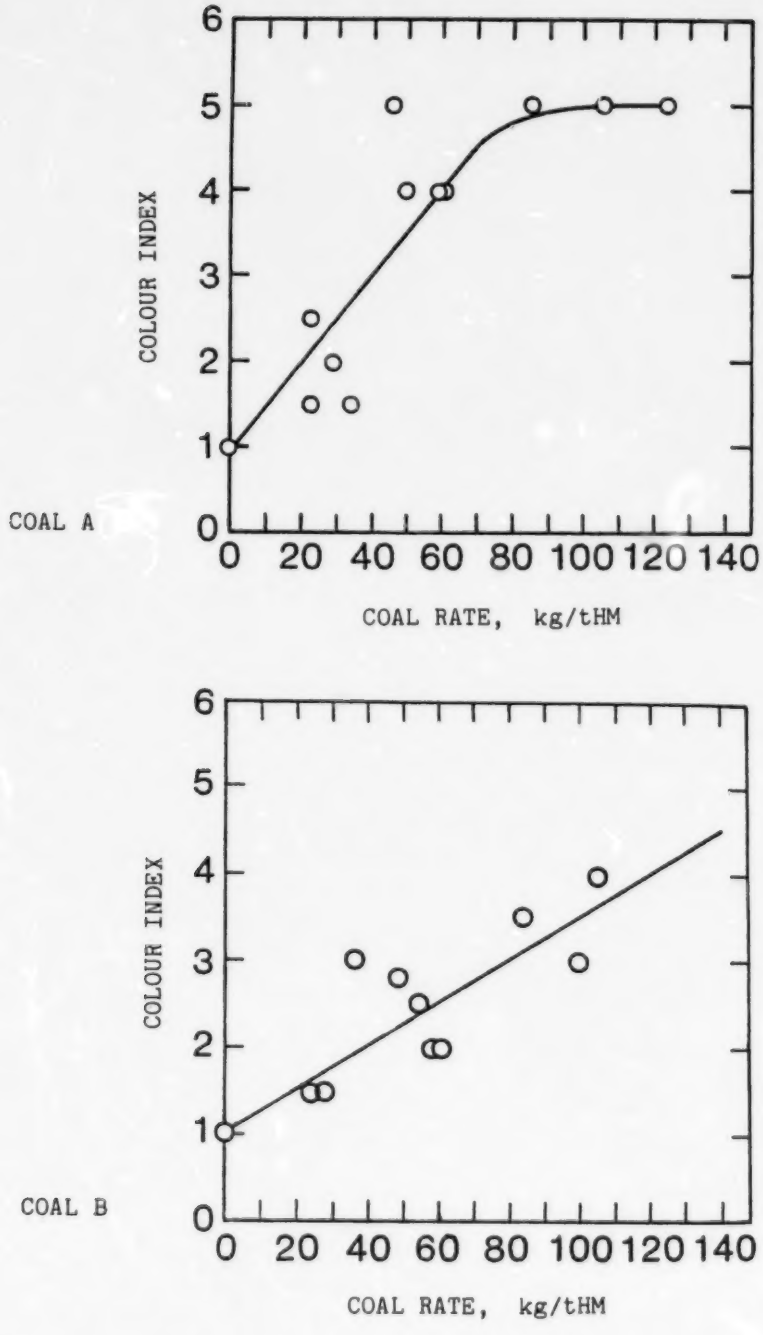


Fig. 63 - Effect of PCI rate on combustion efficiency for two types of coal having different volatile matter content

EVALUATION OF CANADIAN COALS FOR BLAST-FURNACE INJECTION

Canadian coal reserves have been estimated to be about 65 x 10^9t, of which about half is of bituminous rank (2) and occurs mainly in the Rocky Mountains and foothills of Alberta and British Columbia. It constitutes about 10% of the entire world coal reserves. Canadian coal production and export data for 1985 and 1986 are shown in Appendix A, Table A-2 (117).

Canada has a large variety of coals with a substantial range in both ash and volatile levels suitable for blast-furnace injection. Among them, typical coals have been selected for consideration. (Table A-3 (118), A-4, A-5, A-6 (119) present data on anthracite, bituminous, subbituminous, and lignites, respectively.)

ANTHRACITE

Canadian (Mt. Klappan, B.C.) anthracite has a low hydrogen content (2.02%) and consequently carries a higher C:H ratio (44.0) than anthracites reported by U.S. Bureau of Mines with a ratio of 30.0 (24). Having a small cooling effect on a raceway adiabatic flame temperature, it could be beneficial to blast-furnace operation and result in high injection rate. According to Ridgion and Cordier (see Fig. 43) (24), a coal like Mt. Klappan anthracite could be injected at the rate of 15 kg/300 m^3 air to compensate for the 100°C increase in blast temperature and to maintain constant RAFT. Industrial experience (9-12,28) confirms suitability of anthracite for blast-furnace injection.

BITUMINOUS COALS

Volatile Matter Content. Volatiles affect combustion of coal directly and indirectly in the blowpipe-tuyère-raceway system as already discussed. Direct effect is exerted by quantity and composition of volatiles whereas tar yield may be regarded as an indirect effect of volatiles. Theoretically, low-volatile coal favours maximum injection rates. Figure 64 (82) shows the influence of volatiles on coke rate and production obtained by using a material and heat balance model. Ash content is assumed to be constant at 7%.

Two important features may be observed: (a) injection of a high-volatile coal (40%) gives less beneficial coke rate and productivity; and (b) because of a lower cooling effect, the 10-20% coal can be injected at higher rates which thus saves potentially more coke and increases production.

Most Canadian bituminous coals have volatiles in the 20-27% range but a few have higher contents of volatile matter between 30 and 37% (see Appendix A, Table A-4). Although many ironmakers prefer using high-volatile coal injectants, some industrial experience (99) indicates that medium-volatile coal is more suitable because of its more complete burnout in comparison with high-volatile coal. This feature is considered to be associated with higher tar yield of high-volatile coal as discussed earlier.

Also, another study indicates some advantages of low- and medium-volatile coal in relation to the coke replacement ratio (see Fig. 18) (31).

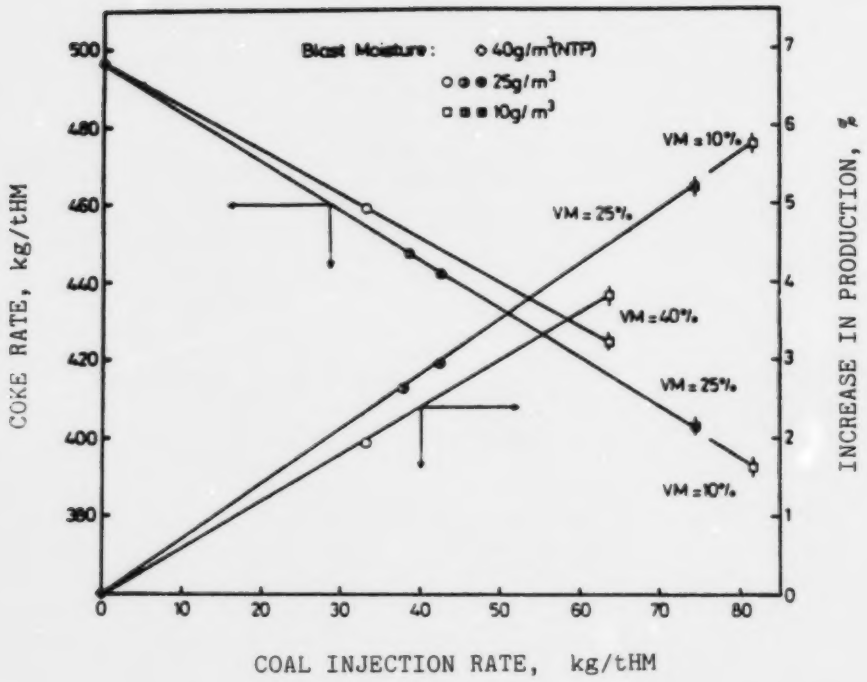


Fig. 64 - Effect of volatile matter content on coal injection rate and productivity

Ash Content. An ash content of 10% is commonly regarded as the higher limit of an acceptable amount of ash input into a blast furnace.

Canadian bituminous coals have ash contents in the narrow range of 2.88 to 10.91% with a few a little higher such as 11.32%, 12.7%, and 17.32% (see Appendix A, Table A-4). In addition, Canadian coals have low alkali contents, close to lower limit of an average alkali content for the coal (1-4%). This property is particularly important because of the detrimental role of alkalis in the blast furnace as discussed earlier.

Sulphur Content. Although desulphurization in the blast furnace is not a technical problem, high sulphur content implies some undesirable operating consequences. Canadian coals have sulphur ranging from 0.19 to 1.72% (see Table 4). This level assures low sulphur in hot metal without the additional cost imposed by an increasing slag volume.

Moisture. As mentioned earlier, according to Japanese data (23), inherent coal moisture affects PC moisture (see Fig. 45). Very low inherent moisture of Canadian coals (0.63-1.72%), except for one coal (see Appendix A, Table A-4), ensures low PC moisture which is of particular importance for transportation and distribution of PC in injection system.

Grindability. Grindability of Canadian coals is very high at 44-94 (see Appendix A, Table A-4) compared with others (usually 10 to 40). This factor is advantageous in coal preparation for PCI.

SUBBITUMINOUS COALS

Subbituminous coals contain high volatiles (35-40%), low ash (6.30-11.30%), and low sulphur (0.22-0.62%) (see Appendix A, Table A-5). In addition, they present relatively high levels of calcium oxide in ash, which may be beneficial in the slagging process. Their high volatiles may be a desirable factor because subbituminous coals produce very low tar during pyrolysis, compared with high-volatile bituminous coals (see Fig. 61). Therefore, a combination of both high volatiles and low tar yield may be potentially an attractive feature from the viewpoint of combustion in the blast furnace. Experimental data are lacking on combustion of subbituminous coals under simulated blast-furnace conditions and investigations are required to establish the burning characteristics.

LIGNITES

A full-scale experiment on lignite injection at ARBED Belval Works, Luxembourg, (61) proved that this kind of fuel could easily be injected. Blast-furnace response was very favourable and showed good productivity compared with hard coal. Also, no major disturbance in the combustion process was observed.

Based on results obtained in Luxembourg, similar Canadian lignites (see Appendix A, Table A-6) can be regarded as beneficial fuels for blast-furnace injection.

FACTORS FAVOURING COAL INJECTION, CONCLUSIONS, AND COST ANALYSIS

The blast furnace is the most energy-intensive stage of steel production. Up to 80% of the energy costs of making steel are incurred here (120). The energy requirement for a given blast furnace is a function of the furnace design, burden properties, and operating parameters. Coke is a major source of energy in the blast-furnace process, but it is costly. In addition, a shortage of coke is predicted with accompanying high prices (120). Dependence on coke is particularly reduced by auxiliary fuel injection.

The factors influencing the selection of injectant are:

- suitability of the blast furnace including the quantity and temperature of hot blast available;
- cost and availability of coke versus the cost and availability of injectant; and
- capital and operating costs for the injection system.

Of all fossil fuels injected into the blast furnace, coal stands out as the fuel with widespread, long-term availability and relatively low cost compared to coke and other potential injectants.

The advantages of coal over other fossil fuels are availability and price, reserves, quality, technological advantages, and cost savings.

Availability and Price. Coal of suitable quality for injection is available in nearly all parts of the world. Internationally, the supply of coal is not as limited and subjected to unpredictable political pressures as are petroleum products. Domestically, Canada has large coal deposits (10% of the world deposits) of various types of coal well suited to blast-furnace injection.

Coal Reserves. Compared with other fossil fuels, coal is considered to be the major fossil fuel of the near future. Known reserves of coal in the world are thought to be adequate for several coming centuries compared with less than a century for oil and natural gas.

Acceptable Coal Quality. Various types of coals (from lignite to anthracite) have been successfully injected (see Table 1).

Technological Advantages.

(a) Coal injection alters the image of the reduction process in favour of indirect reduction.
(b) The highest rate of indirect reduction (59%) occurs when coal is injected with the lowest direct reduction rate (34%) compared to oil injection and all-coke operation (see Fig. 10).
(c) The rate of solution loss reaction is accordingly lowest for coal injection (see Fig. 14), which decreases the thermal requirements to produce a given amount of iron.
(d) Decrease in the rate of solution loss reaction is believed to decrease the weakening of coke caused by this reaction and, consequently, to improve burden permeability.
(e) Injection of coal is important in controlling the energy balance of the furnace combustion zone.

(f) Coal has the highest C:H ratio among other fossil auxiliary fuels and, consequently, the smallest cooling effect on the raceway (see Fig. 15).
(g) Coal can be injected in larger quantities than other fuels while maintaining optimum RAFT (see Figs. 13, 14, and 43).
(h) Because of larger acceptable injection rate, coal generates higher total coke replacement ratio than oil and natural gas (see Figs. 20 and 65) (121).
(i) According to theoretical considerations and full-scale experiments, coal can replace 30 to 40% of coke without negative operating consequences (see Appendix A, Table A-7).
(j) According to available data (see Appendix A, Table A-7), decrease in coke rate is:
    - an average 15%;
    - the largest (anthracite) 38% (Shoudu Steel Corp., China);
    - for lignite 7.4%; and
    - for granular coal 8.6%.
(k) By reducing the proportion of coke in charged materials, the proportion of iron-bearing material increases which improves productivity of the furnace (see Appendix A, Table A-7).
(l) According to available data (see Appendix A, Table A-7), increase in productivity is:
    - an average 8.7%;
    - the largest 30% (Shoudu Steel Corp., China);
    - for lignite 7.4%; and
    - for granular coal 16.7%.

Cost Savings. The replacement of greater quantities of coke because of its significant cost is a major factor in reducing cost of iron production. The economy of the coal injection depends on local conditions such as coke plant facilities, the price and availability of coal and coke, as well as market possibilities for excess coke-oven gas.

Based on ARMCO experience, cost savings possible by the use of coal injection are presented in Tables 7 and 8 (120). Table 7 illustrates cost savings available when coal is considered to substitute coke. In Table 8, coal is considered to replace oil. In both tables, installation costs have not been taken into account.

The savings as a result of injecting coal are: U.S. $5.68/tHM when applied to all-coke furnace operation (see Table 7) and U.S. $10.18/tHM when coal replaces oil (see Table 8).

For a hypothetical furnace producing 2000 t/day of iron, the annual savings are: U.S. $4 146 000 to replace coke and U.S. $7 431 400 to replace oil which gives $5 389 000 and $9 660 820 in Canadian funds, respectively.

This simple replacement savings does not take into account improved productivity and stabilization of furnace operation.

Savings are shown graphically in Figures 66 and 67 (120) for coke and oil replacement, respectively. It is based on two assumptions: (a) that 1 kg coal replaces 1 kg coke; and (b) that 1.2 kg coal replaces 1 kg oil.

Table 7 - Cost savings per tonne of iron when coal injection replaces coke

Assumptions:	
•Blast-furnace capacity	5000 t/day (1 750 000 t/year)
•Present fuel rate	500 kg/tHM
•Coke ash	9%
•Coal ash	6%
•Fuel cost : Coke	$120/t*
Coal	$60/t
•Cost of injection	$8/t of coal
•Coke replacement	20%
Calculation:	
Replacement ratio	R = 1.48 - 0.666 (6% coal ash)/(9% coke ash)
	R = 1.04 kg coke saved/kg coal injected
Coal injected	500 kg/tHM x 0.20 = 100 kg/tHM
Coke replaced	100 x 1.04 (R) = 104 kg/tHM
Remaining coke	500 kg/tHM - 104 kg/tHM = 396 kg/tHM
Fuel cost base at 100% coke rate (Coke)	500 kg at $120/t = $60.00/tHM
Fuel cost with coal injection	396 kg coke at $120/t = $47.52/tHM
	100 kg coal at ($60 + 8)/t = $6.80/tHM
Total fuel cost	$54.32/tHM
Cost savings	$60.00 - 54.32 = $5.68/tHM

* All $ are U.S. dollars.

Table 8 - Cost savings per tonne of iron when coal replaces oil injection

Assumptions the same as Table 7 plus:	
•Initial fuel usage	420 kg coke/tHM
	67 kg oil/tHM
•Oil cost	$230/t*
•Oil replacement ratio	1.2 (i.e., kg of coke saved per kg oil injected)
Calculation:	
Replacement ratios	Oil = 1.2 kg coke saved/kg of oil injected
	Coal (6% ash) = 1.04 kg coke saved/kg of coal injected
Equivalent coal to replace 67 kg/t oil	67 kg/t x 1.2/1.04 = 77 kg/t coal
Cost of injected oil	67 kg/t at $230/t = $15.41/tHM
Cost of injected coal	77 kg/t at ($60 + 8)/t = $5.23/tHM
Cost savings coal	$15.41 - 5.23 = $10.18/tHM

*All $ are U.S. dollars.

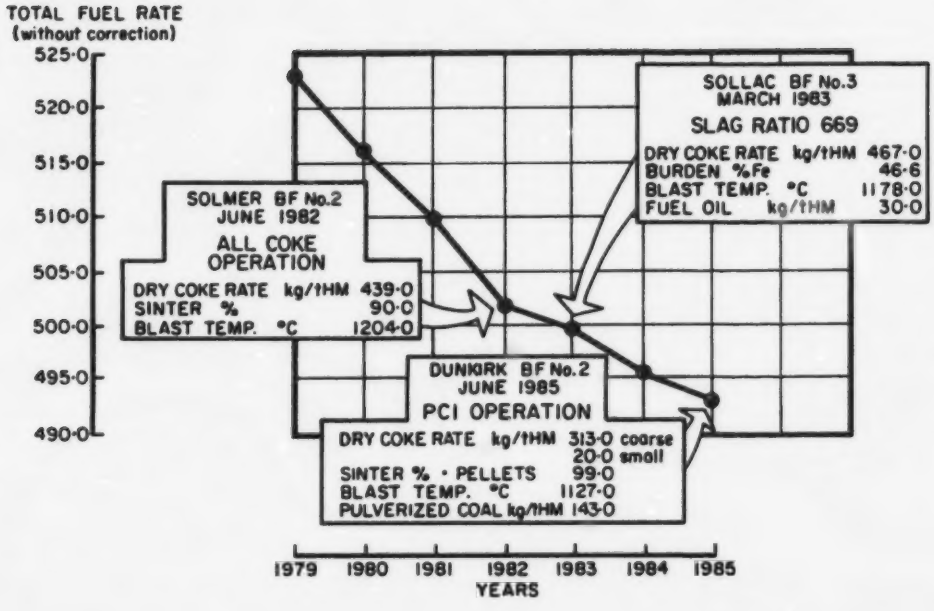


Fig. 65 - Evolution of fuel rate in France

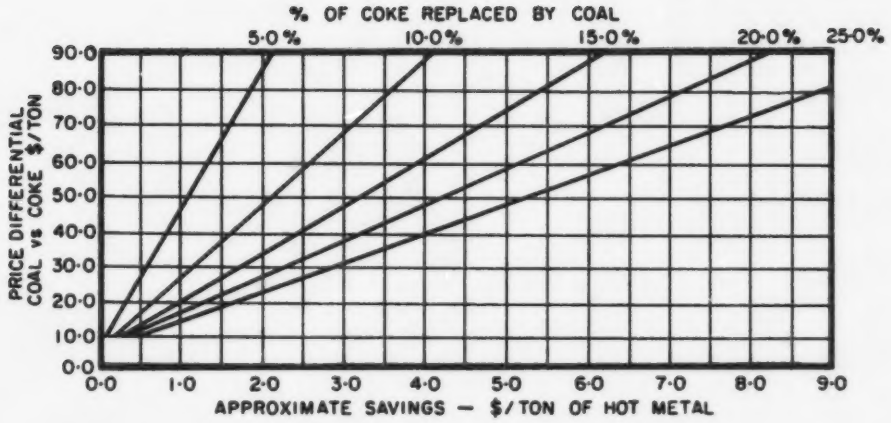


Fig.66 - Savings when coke is replaced by coal

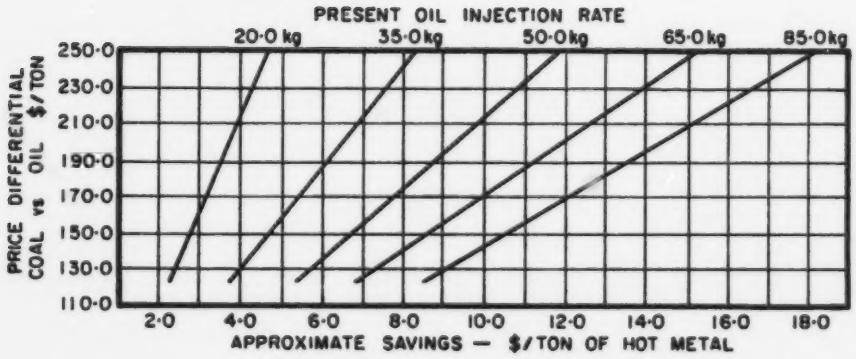


Fig. 67 - Savings when injected oil is replaced by coal

Keenan and Morrison give approximated savings of U.S. $3/tHM when coal replaces oil, with a payback period of 3.8 years (122).

Another source (48) gives savings of 9 DM/tHM (West German funds) when coal is injected versus an all-coke operation. Return of investment is 30, 17 and 13 months for coal injection rates of 55, 80 and 100 kg/tHM, respectively.

Construction Costs. Estimated construction costs of a typical PCI system based on the ARMCO - Babcock & Wilcox (Amanda) system for about 20 tonnes of injected coal per hour are as follows (25):

	(U.S. $ million)	(%)
Raw coal system	1.2	8
Grinding and collection	5.0	33
Injection system	4.0	27
Auxiliaries	2.5	17
Controls	2.3	15
Total	15.0	100

Mechanical systems. Recently developed pneumatical systems (1,40,48) ensure an accurate control of coal distribution and injection to individual tuyères which is particularly important in case of pressure fluctuation in the blowpipe-tuyère-raceway system.

RESEARCH NEEDS

Although coal injection technology is becoming well established, many problems require investigation, particularly those related to coal combustion. For a better understanding and optimization of the major factors influencing coal injection and blast-furnace operation, research is required in five key areas.

COMPUTER MODELLING AND PROCESS SIMULATION

Motivation. Blast-furnace operation, particularly as it is affected by coal injection, is an extremely complex interplay of processes and mechanisms in which many variables are involved. Important factors include: coal type (VM, ash), combustion efficiency of coal, blast conditions, flame temperature, coal injection rate (stoichiometric ratio), amount of replaced coke, reduction process (solution loss, indirect), composition of burden materials, and hot metal and slag composition.

Objective. The objective is to determine the most beneficial operating conditions.

Methodology:

- material and energy balance method;
- formulation of simultaneous equations involving mass balance (Fe, C, O_2, H_2) and energy balance (overall, combustion zone-flame temperature);
- use of Canadian data; and
- factors for consideration: coal rate, coal type, blast conditions, coke rate, and reduction process.

COAL COMBUSTION CHARACTERISTICS

More study is needed on the influence of coal properties (VM, tar, soot) and combustion conditions on combustion efficiency under blast-furnace conditions.

Motivation. Although some research has been reported, insufficient data yet exists to identify coal properties that ensure desired combustion efficiency. To accomplish this task, three studies could provide data on all stages of coal combustion.

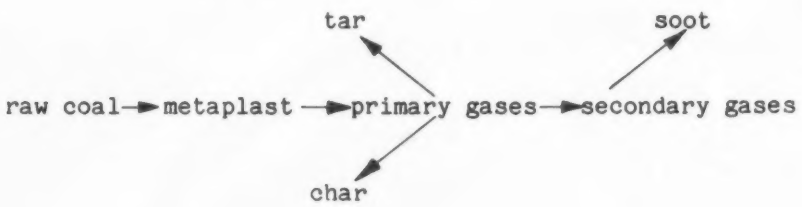
Study of Kinetics of Coal Pyrolysis

Motivation. There is a lack of pyrolysis data under blast-furnace conditions.

Objectives:

- to determine tar yield as a function of coal properties; and to determine the influence of minerals on the evolution of coal pyrolysis products (tar) and their effect on coal burnout.

Methodology. The Chermin and van Krevelen model of coal pyrolysis (83) is assumed.



Laboratory experiments would use reaction temperatures between 1000° and 1300°C and heating rates of 10^{5}° to 10^{6}°C/s.

Study of Gas-Phase and Heterogeneous Coal Combustion

Motivation. There is a lack of data on the influence of VM and tar on coal burnout in the blowpipe-tuyère-raceway, and there are no quantitative data on soot formation and its influence on coal burnout.

Objectives:

- to determine the influence of pyrolysis products (VM, tar) on combustion;
- to establish the mechanism of soot formation, its combustion characteristics and influence on coal burnout; and
- to determine the influence of injection point location and mixing mode on combustion efficiency and ash deposition as a function of coal type.

Methodology. Experiments in a combustion chamber simulating a blast-furnace environment:

- blast temperature 1000° to 1300°C;
- blast velocity 150 to 300 m/s;
- stoichiometric ratio 1.0 to 2.5; and
- oxygen enrichment 21 to 25%.

Study of Coal Combustion in the Blowpipe-Tuyère Raceway

Objectives:

- to confirm laboratory results; and
- to establish criteria for coal evaluation and selection for blast-furnace injection.

Methodology:

- trial on an operating blast furnace injecting coal into a single tuyère.

COMBUSTION OF GRANULAR VS PULVERIZED COAL

Motivation. As yet, no definitive answer is available as to whether pulverized or granular coal should be injected.

Objectives:

to identify a more beneficial version of coal injection.

Methology. Laboratory experiments and theoretical consideration would include economic analysis.

COKE BEHAVIOUR DURING COAL INJECTION

Motivation. There is an unconfirmed hypothesis that coke weakening is reduced when coal is injected.

Objectives:

- to establish relationship between solution loss reaction and degradation of coke; and
- to determine properties of coke required when coal is injected.

Methodology. Theoretical analysis would be combined with experiments made under simulated conditions.

COMBUSTION CHARACTERISTICS OF CANADIAN COALS FOR BLAST-FURNACE INJECTION

Motivation. Data are lacking and the use of coal injection by major Canadian customers has increased (Japan, 70% increase in 1986 compared to 1985).

Objectives:

- to characterize combustibility of Canadian coals (anthracite, bituminous, subbituminous, and lignite); and
- to increase competitiveness of Canadian coals in relation to others by providing complete data to customers.

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APPENDIX A

COAL ANALYSIS AND BLAST-FURNACE DATA

Table A-1 - Differences between Amanda and Bellefonte (ARMCO-Babcock & Wilcox) coal injection systems

Item	Bellefonte	Amanda
Pulverized system atmosphere	Low oxygen recirculated	Air once through
Primary circulation fan	High pressure (high RPM)	Low pressure (low RPM)
Pulverizer off line (failure)	Loss of 1/2 capacity	No change of rate for 5 hours
Exhaust gas cleaning	Wet scrubber	Bag filter
Injection air source	Booster on main blower	Separate air compressor
Raw coal feed system	Look hoppers, high-pressure feeder	Standard feeder
Injection rate control	Feeder speed to pulverizer	Pressure change of feed

Table A-2 - Canadian coal production and export (1985, 1986)

	Production (millions of tonnes)					
	Metallurgical		Thermal		Total	
Province	1985	1986	1985	1986	1985	1986
Nova Scotia	0.4	0.4	2.4	2.5	2.8	2.9
New Brunswick	-	-	0.6	0.5	0.6	0.5
Saskatchewan	-	-	9.7	8.3	9.7	8.3
Alberta	4.4	4.5	20.2	20.5	24.7	25.0
British Columbia	19.4	17.3	3.6	3.8	23.0	21.1
Total	24.2	22.2	36.5	35.6	60.8	57.8

	Exports	
Product	1985	1986
Metallurgical	22.4	21.6
Thermal	4.9	4.4
Total	27.3	26.0

Table A-3 - Characteristics of Canadian anthracite

Comp/Coalfield	Coal rank	Proximate analysis (dry)			Ultimate analysis (dry)			Heating value MJ/kg	Inher. moist.	Grind. index	Ash analysis				FSI
		Ash	V M	F C	C	H	S. tot	C:H			SiO_2	Al_2O_3	CaO	Na_2O K_2O	
Gulf Canada/ Mt. Klappan, B.C.															
Coarse Premium Prod.		5.73	6.27	88.00	88.39	2.02	0.47	32.63 / 43.80	0.70	30	48.09	26.95	6.06	3.26	-
Fine Premium Prod.		7.00	6.85	86.15	86.28	2.71	0.51	32.11 / 31.84	0.86	41	53.52	25.93	4.35	3.02	-

VM - Volatile matter
FC - Fixed carbon

Table A-4 - Characteristics of Canadian bituminous coals

Comp/Coal-field	Coal rank	Proximate analysis (dry)			Ultimate analysis (dry)			Heating value MJ/kg	Inher. moist.	Grind. index	Ash analysis				FSI
		Ash	V M	F C	C	H	S. tot.	C:H			SiO_2	Al_2O_3	CaO	Na_2O K_2O	
Luscar Ltd./ Coalspur, Alta.	Bitum H V	11.32	33.09	55.59	70.05	4.48	0.28	27.78 / 15.6	-	44	58.28	18.73	6.63	1.53	-
Smokey River, Alta.	Bitum L V	7.12	17.46	75.42	84.98	4.28	0.45	33.83 / 19.8	0.71	94	53.31	28.08	3.99	1.90	4.5
Westar Min./ Crowsnest, Alta.	Bitum M V	9.95	21.13	68.92	81.73	4.44	0.27	32.43 / 18.4	0.80	86	60.41	27.69	1.89	0.41	6.0
Crowsnest/ Elk Valley, B.C.	Bitum M V	17.32	20.62	62.06	71.20	3.78	0.37	28.35 / 18.8	1.32	77	60.02	30.12	0.90	0.96	1.5
Denison Mines/ Peace R., B.C.	Bitum M V	12.75	23.09	64.16	75.82	4.05	0.37	30.13 / 18.7	1.30	78	60.05	22.29	3.90	1.96	1.0

Table A-4 (Cont'd)

Comp/Coalfield	Coal rank	Proximate analysis (dry)			Ultimate analysis (dry)			Heating value MJ/kg	Inher. moist.	Grind. index	Ash analysis				
		Ash	V M	F C	C	H	S. tot.	C:H			SiO_2	Al_2O_3	CaO	Na_2O K_2O	FSI
Fording Coal/ Elk Valley, B.C.	Bitum H V	6.26	30.17	63.57	80.58	4.84	0.60	33.11 / 16.6	1.16	92	52.16	27.61	3.31	0.73	7.5
Westar Min./ Elk Valley, B.C.	Bitum H V	6.43	27.39	66.18	81.64	4.68	0.47	33.23 / 17.4	1.06	92	52.97	29.40	3.05	0.83	7.0
Cardinal R./ Cadomin, Alta.	Bitum M V	9.78	22.07	68.15	81.69	4.38	0.20	32.65 / 18.5	0.87	80	48.48	24.77	7.68	1.78	6.5
Cape Breton/ Sydney, N.S.	Bitum H V	3.01	36.47	60.52	82.36	5.26	1.49	35.19 / 15.6	1.25	60	26.40	16.79	1.24	1.50	8.0
N.B. Coal/ Minto, N.B.	Bitum H V	10.25	35.27	54.50	76.34	5.02	4.82	32.92 / 15.2	0.92	63	29.74	11.96	1.34	2.78	7.0
Cape Breton/ Sydney, N.S.	Bitum H V	2.88	37.90	59.22	82.66	5.43	1.63	35.01 / 15.2	1.25	60	22.36	14.64	1.22	1.38	8.0
Seminco Inc./ N.S.	Bitum H V	5.36	34.48	60.16	79.12	5.48	1.58	33.54 / 14.44	1.72	63	43.34	20.52	1.55	2.55	7.5
Gregg River/ N.S.	Bitum H V	9.95	21.14	68.91	81.56	4.39	0.31	32.71 / 18.6	0.94	85	54.71	25.32	4.34	1.73	5.0

HV - High volatile
LV - Low volatile
MV - Medium volatile

Table A-5 - Characteristics of Canadian subbituminous coals

Comp/Coalfield	Coal rank	Proximate analysis (dry)			Ultimate analysis (dry)			Heating value MJ/kg	Inher. moist.	Grind. index	Ash analysis				
		Ash	V M	F C	C	H	S. tot.	C:H			SiO_2	Al_2O_3	CaO	Na_2O K_2O	FSI
Forestburg/ Battle R., Alta.	C	6.30	40.13	53.57	68.69	4.47	0.47	26.45 / 15.4	-	34	36.03	14.22	18.78	0.56	-
Manalta Coal/ Shearness, Alta.	C	8.30	39.63	52.07	65.54	4.40	0.62	25.27 / 14.9	-	39	33.09	19.31	18.39	1.77	-
Manalta Coal/ Wabamun, Alta.	C	11.30	35.76	52.44	64.35	4.03	0.22	24.59 / 16.0	-	42	44.10	23.27	14.74	4.04	-
Manalta Coal/ Wabamun, Alta.	C	9.37	39.18	51.45	66.39	4.41	0.47	25.78 / 15.0	-	36	41.24	16.61	20.06	1.21	-
Forestburg/ Battle R., Alta.	C	7.41	38.69	53.90	67.10	4.50	0.49	25.87 / 14.9	-	34	41.79	15.38	15.10	4.73	-

Table A-6 - Characteristics of Canadian lignites

Comp/Coalfield	Coal rank	Proximate analysis (dry)			Ultimate analysis (dry)			Heating value MJ/kg	Inher. moist.	Grind. index	Ash analysis				
		Ash	V M	F C	C	H	S. tot.	C:H			SiO_2	Al_2O_3	CaO	Na_2O K_2O	FSI
Bienfait Coal/ Estevan, Sask.	A	10.22	40.11	49.67	63.63	4.34	0.42	24.67 / 14.7	-	58	25.61	19.89	18.56	10.45	-
Manalta Coal/ Estevan, Sask.	A	10.05	42.16	47.79	65.29	4.38	0.96	25.20 / 14.9	-	51	23.72	12.63	20.50	10.86	-
Manalta Coal/ Estevan, Sask.	A	10.28	41.34	48.38	64.21	4.50	0.40	24.49 / 14.3	-	60	27.36	18.86	19.15	11.74	-

Table A-7 - Coal injection operating data

Ref.	Works	Furnace dimension, m^3	Injection system	Coal Type size	Coal VM	Coal FM	Coal Ash	Coal S	Coal rate, kg/tHM	Coal rate, kg/tHM	Decr. in coke rate, %	Repl. ratio	Blast temp. °C	Blast rate m^3/h	Product. rate t/day	Incr. in prod. rate, %	Slag basic	CO/CO_2
(8) (123)	Hanna Furnace, National Steel Corp.	no. 2 464	Petrocarb	no injection					-	728	-	-	790	66 270	613		0.96	1.58
				L V / P C	17.6	74.9	7.5	0.9	142	657	15.5	0.86	803	66 270	612	-	0.99	1.62
(8) (123)	Hanna Furnace, National Steel Corp.	no. 2 464	Petrocarb	no injection					-	795	-	-	706	66 270	613		0.96	1.62
				H V / P C	40.0	55.6	4.4	1.1	132	670	15.7	0.95	815	66 270	613	-	1.01	1.70
(13) (123)	Weirton, National Steel Corp.	no.3 1332	Koppers	no injection					-	620	-	-	983	123 322	1619	-	1.18	1.47
				H V / P C	39.6	54.7	13.9	0.1	96	539	13.1	0.85	983	114 189	1540	-4.9	1.12	1.54
(10) (63)	Chasse France	no. 2 176		no injection					-	710	-	-	750	-	162	-	1.08	0.43
				H V / P C	34.5	-	7.9	0.8	109	572	10.4	1.03	833	-	173	6.4	0.94	0.50
				L V / P C	6.6	-	9.3	0.6	132	550	22.5	1.00	837	-	212	24.0	1.01	0.53
(11) (12) (12)	Stanton and Staveley, U.K.	no. 5 543	Petrocarb	no injection					-	782	-	-	850	47 580	461	-	1.26	3.38
				H V / P C	32.5	50.7	7.7	0.7	67	710	9.2	0.93	910	52 680	506	10.0	1.22	3.30
				H V / P C	35.4	52.2	5.7	1.5	74	710	9.2	1.02	950	52 680	507	10.0	1.22	3.12

Table A-7 - (Cont'd)

Ref.	Works	Furnace dimension, m^3	Injection system	Coal type / size	Coal V M	Coal F M	Coal Ash	Coal S	Coal rate, kg/tHM	Coal rate, kg/tHM	Decr. in coke rate, %	Repl. ratio	Blast temp. °C	Blast rate m^3/h	Product. rate t/day	Incr. in prod. rate, %	Slag basic	CO/CO_2
(12) (36)	Stanton and Staveley, U.K.	no. 5 543	Petrocarb	no injection					-	920	-	-	850	51 000	320	-	1.25	3.07
				anthr. P C	7.1	83.0	8.7	0.81	135	790	14.0	1.00	815	51 000	396	12.6	1.23	2.77
(36)	Stanton and Staveley, U.K.	no. 5 543	Petrocarb	no injection					-	920	-	-	830	54 360	446	-	1.27	3.07
				H V P C	34.2	58.1	5.7	1.4	182	740	19.6	1.01	935	54 000	409	-8.3	1.31	3.26
(14)	Ashland	Bellefon. 1488	B & W	H V P C	37.0	57.4	5.6	0.7	132	439	-	0.78	931	164 401	2093	-	1.14	-
				P C	-	-	-	-	81	481	-	-	957	15 300	2128	-	0.90	1.17
(125)	ARMCO	Amanda 2039	B & W	H V P C	35.5	61.0	3.5	0.7	85	486	-	-	884	225 480	3361	-	0.90	1.13
(28)	Shoudu Steel Corp., China	1034	Chinese	no injection					-	587	-	-	1022	75 600	2037	-	1.06	-
				anthr. P C	8.3	76.8	14.4	0.4	240	361	38.0	0.85	1126	85 932	2539	24.6	1.03	-
		576	Chinese	no injection					-	587	-	-	1025	-	1135	-	-	1.71
				anthr. P C	7.2	78.9	13.9	0.1	216	365	37.8	0.87	1120	83 100	1436	21.0	1.01	1.19
(60)	Karaganda USSR		Karaganda	no injection					-	598	-	-	1065	158 760	2825	-	1.01	1.47
				L V P C	18.0	-	32.9	1.1	61	561	6.2	0.63	1074	157 423	2797	-1.0	1.02	1.34

Table A-7 - (Cont'd)

Ref.	Works	Furnace dimension, m^3	Injection system	Coal type/size	Coal V M	Coal F M	Coal Ash	Coal S	Coal rate, kg/tHM	Coal rate, kg/tHM	Decr. in coke rate, %	Repl. ratio	Blast temp. °C	Blast rate m^3/h	Product. rate t/day	Incr. in prod. rate, %	Slag basic	CO/CO_2
(67)	Donecк, USSR			no injection					n.gas 75.2 m^3	510	-	-	1076	121 260	1782	-	1.28	-
			Donecк	-	-	-	-	-	61/68 m^3 ng	455	-	0.67	1062	119 940	1841	-	1.29	-
(57)	Zaporozstal, USSR			no injection					n.gas 79.6 m^3	512	-	-	1141	142 800	2126	-	1.22	1.64
			Zaporozstal	anthr. P C	6.1	72.3	20.3	1.3	21/81.5 m^3	497	-	-	1125	140 100	2130	-	1.22	1.71
(50) (61)	ARBED - Belval,	A		no injection					-	5553	-	-	979	132 000	1980	-	-	-
			ARBED-Wurth	lign. P C	44.0	41.0	4.0	0.5	76	512	7.4	0.54	1111	-	2126	7.4	-	-
	Luxembourg	1376	ARBED-Wurth	L V P C	12.0	73.0	13.5	1.0	53	506	8.5	0.81	1132	-	2111	6.2	-	-
(23) (46)	Oita Nippon St., Japan	no. 1 4158		no injection					-	469	-	-	1281	322 183	7068	-	-	-
			B & W	H V P C	32.5	-	7.5	-	52	402	14.3	1.11	1291	303 102	7484	5.9	-	-
(20) (95)	Kokawa Kobe St., Japan	no. 2 1845		no injection					-	491	-	-	1098	-	7068	-	-	-
			Petrocarb	-	-	-	-	-	50	400	10.4	0.91	1113	-	6950	-	-	-

Table A-7 - (Cont'd)

Ref.	Works	Furnace dimension, m^3	Injection system	Coal type size	Coal V M	Coal F M	Coal Ash	Coal S	Coal rate, kg/tHM	Coal rate, kg/tHM	Decr. in coke rate, %	Repl. ratio	Blast temp. °C	Blast rate m^3/h	Product. rate t/day	Incr. in prod. rate, %	Slag basic	CO/CO_2
(53)	Scunthorpe British Steel Corp.,	Victoria 1473	B.S.C.	no injection					-	514	-	-	885	127 917	2346	-	0.93	-
				H V granul.	32.2	-	7.1	1.2	51	470	8.6	0.89	903	139 530	2738	16.7	1.00	-
(54)	U.K.	Queen Mary 1300	B.S.C.	no injection					-	489	-	-	844	117 700	2191	-	0.96	-
				H V granul.	-	-	3.5	1.5	28	454	7.1	0.89	884	119 483	2337	6.7	0.96	-
(51) (52)	Usinor, France	no. 2 1600	ARBED - Wurth	L V P C	-	-	-	-	78	406	-	0.84	1111	168 200	3935	-	1.16	1.05
(128)	Ucknage, France	no. 3 710	Sprunck-Ucknage	no injection					-	465	-	-	1004	-	-	-	-	-
				H V P C	31	-	7	-	55	408	12.2	0.85	1006	-	-	-	-	-
(18) (129)	Chiba Kawasaki St., Japan	no. 5 2584	Kawasaki	no injection					-	525	-	-	1026	-	-	-	-	-
				H V P C	34.2	55.0	9.9	0.6	24	497	5.3	0.91	997	-	-	-	-	-
(43)	Hoogovens Steel, Holland	no. 6 2400	B & W	no injection					-	533	-	-	1022	260 820	4543	-	-	1.09
				H V P C	33.6	-	5.7	0.8	90	416	21.9	0.87	1105	247 452	4628	1.0	-	1.08
		no. 7 3520		no injection					-	491	-	-	1114	339 840	7114	-	-	1.03
				H V P C	33.6	-	5.1	0.8	80	414	15.7	0.83	1231	345 060	7002	-1.9	-	1.04

Ref.	Works	Furnace dimension, m^3	Injection system	Coal type size	Coal V M	Coal F M	Coal Ash	Coal S	Coal rate, kg/tHM	Coal rate, kg/tHM	Decr. in coke rate, %	Repl. ratio	Blast temp. °C	Blast rate m^3/h	Product. rate t/day	Incr. in prod. rate, %	Slag basic	CO/CO_2
(47) (48)	Svenska St., Lulea, Sweden	no. 2 1235	Klockner	no injection					-	464	-	-	-	-	3334	-	0.95	-
				M V P C	26.5	-	8.7	0.5	67	398	14.2	1.00	-	-	3828	14.8	0.92	-